STUDY OF MECHANICAL COALESCING FOR PETROLEUM EMULSIONS

DSS CONTRACT No. 23440-6-9146/01-SQ

TASK 1 INTERIM REPORT: PRIOR STUDIES SURVEY

BY

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76 pp

MICROMEDIA

SUMMARY

The investigation of the state-of-the-art of passive mechanical emulsion breaking and separation described in this report comprised Task 1 of Supply and Services Canada Study of Mechanical Coalescing for Petroleum Emulsions (DSS Contract No. 23440-6-9146/01-SQ), being carried out under the auspices of the Devon Coal Research Laboratories, Devon, Alberta. All recognized passive techniques for mechanically breaking emulsions of crude oil and water were considered in this study. Passive mechanical techniques are those methods which rely on the interaction of a physical, normally solid, medium with the emulsion to alter the characteristics of the emulsion and so induce a separation of the phases - an interaction analogous to that of a catalyst in a heterogeneous chemical reaction. Other classes of methods were considered only in potential combination with such a passive coalescing method, therefore.

The current state of knowledge on these techniques was examined particularly with regard to the separation of emulsions of crude oils and water. Highly viscous and "tight" (extremely stable) emulsions with a high water content often result in the production of heavy crude oils and bitumens from enhanced recovery projects (steam flood, huff-and-puff, in-situ combustion, etc.). This is due partly to the typically high asphaltene fraction of such oils

and partly to the entrainment of clays and siliceous fines in the produced fluid, all of which play a demonstrable role in the stabilization of crude oil emulsions. A method for coalescing such an emulsion must therefore also address the concurrent problems of produced fines handling and the robustness of the droplet interfacial surface.

This survey of the patents and scientific literature concerning mechanical emulsion coalescence has revealed that, not surprisingly, the majority of the process studies have been conducted with idealized (easy) systems: slightly stable or even highly unstable emulsions of light oil fractions and water which are broken fairly readily under quiescent settling conditions, or with trace quantities of light oil fractions in water. Emulsions of heavy crude oils and bitumens have been examined mainly by surface chemists investigating the mechanisms of emulsion stabilization and chemical means for inducing coalescence. Thus, from a process perspective, a significant gap exists in the body of knowledge on the treatment of real, produced emulsions with passive mechanical coalescing methods. The remaining phases of this study will significantly bridge this gap.

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NOMENCLATURE

Variables

a_e	effective acceleration, m/s^2
d_p	droplet diameter, m
E	electrical potential gradient, V/m
g	gravitational acceleration, 9.8087 m/s^2
K	permittivity of continuous phase, F/m
k_1	first order coalescence rate constant, s^{-1}
N	droplet population density, m^{-3}
N_o	initial droplet population density, m^{-3}
r	radius, m
t	time, s
u_t	droplet terminal settling velocity, m/s
ζ	droplet-fluid zeta potential, V
μ_c	continuous phase viscosity, $Pa \cdot s$
ρ_c	continuous phase density, kg/m^3
ρ_d	dispersed phase density, kg/m^3
ω	rate of rotation, s^{-1}

Country Codes

BE	Belgium
CAN	Canada
EGR	German Democratic Republic
EP	European Patent
FR	France
GB	United Kingdom of Great Britain
JA	Japan
NL	Netherlands
SU	Union of Soviet Socialist Republics
USA	United States of America
WGR	Federal Republic of Germany

SECTION 1

INTRODUCTION

1.1 Scope of Investigation

This review was undertaken as Task 1 of Supply and Services Canada "Study of Mechanical Coalescing for Petroleum Emulsions" (DSS Contract No. 23440-6-9146/01-SQ). This phase of the overall study was intended to fulfill two functions: (1) to establish the state-of-the-art in relation to the development of mechanical emulsion coalescing techniques, especially with regard to prior work concerning the same or similar fluids, and (2) to indicate promising directions for investigation in Task 2 of the study - the laboratory investigation phase - and potential solutions for problems encountered there.

1.2 Sources of Information

Sources of information considered in the course of this investigation were fourfold:

- scholarly publications (books, journals, conf. proceedings)
- government research reports, technical papers, bulletins, *etc.*
- patents (abstracts)

- other information (including corporate promotional literature)

The time allocated to this phase of the study was the chief factor in precluding closer examination of the patent literature. In most cases - especially in the case of Canadian patents - the abstracts published by patent offices include the major claims (or summaries thereof) of the invention as well as pertinent drawings. Hence, the innovation represented by the patent could usually be understood from the abstract alone, whereas full patents would also provide details of the realization of the invention and the tests carried out. The one month period allotted for this phase of the study was sufficient only to specify the patents of interest and obtain their abstracts.

A limit of 20 years was placed on the age of patents to be examined, for two reasons. First, older patents would either be renewed - if effective - within the timeframe of interest, in which case they would be turned up in the search process, or abandoned, in which case they would have been of limited interest anyway. Secondly, the scientific developments which aroused the initial interest leading to this study were made within that timeframe. Some older literature was also examined, however - mainly to obtain the historical perspective on passive mechanical coalescence of petroleum emulsions.

The initial search for recent publications was carried out on-line, utilizing a total of five databases:

- API-PAT (American Petroleum Institute: patents abstracts)
- API-LIT (American Petroleum Institute: literature survey)
- TULSA (Petroleum Abstracts - Tulsa: patents and literature)
- COMPENDEX (Engineering Index: literature survey)
- CHEM-SEARCH (Chemical Abstracts: patents and literature)

Keywords used for the first four databases were quite specific: "coalesce", "coalescer", "coalescing". The CHEM-SEARCH database, being the most extensive, was searched generally for any combination of "emulsion" and "breaking", "coalescing", or "separating" (with any possible suffix on keywords). These searches yielded in excess of 1000 individual references. A simultaneous manual search of local sources provided some further references of a general nature concerning emulsions. These references were then reviewed for applicability, interest, and availability (again, time constraints precluding obtaining these references from other than local sources) and the reduced list - the primary search list - was then searched out, obtained, and reviewed. A secondary search list was prepared from keynote references in the primary search list, and these additional references were also obtained as available and reviewed prior to the preparation of this report.

1.3 Terminology

Some basic terminology is established here. Emulsions of hydrocarbon liquids and water can exist with either phase dispersed in the other. The dispersed phase exists as discrete droplets distributed in some manner within the body of the second phase - the continuous phase. Thus, an emulsion consisting of oil droplets dispersed in water is referred to as an oil-in-water, oil-water, or **O/W** emulsion. The latter is the most concise terminology and will be used for the remainder of this report. Conversely, an emulsion of water droplets dispersed in a continuous body of hydrocarbon liquid is referred to as a **W/O** emulsion. The terms "internal phase" and "external phase", while not unclear, are less descriptive than **continuous phase** and **dispersed phase**, and the latter terms are preferred. Other, more opaque terminology exists, especially in the older literature. Expressions such as "invert emulsion" and "reverse emulsion", which appear synonymous while referring to differing dispersion types, have now fortunately almost disappeared from usage. "Wax emulsion" and "polymer emulsion", which refer to specific colloidal suspensions, have largely been dropped from the lexicon. An emulsion is recognized as a liquid-liquid entity.

More recent terminology attempts to classify emulsions (of both types) on the basis of emulsion stability or other physical characteristics. Dispersion, emulsion (unstable, semi-stable, quasi-stable, fairly or moderately stable, and

stable) and microemulsion, are all terms which have come into use - and abuse - in order to discriminate among the behaviours of differing emulsions. There is, as always, a great degree of overlap between the definitions used by the various investigators because of the perennial problem of discretization of a continuum (a spectrum) of behaviours or characteristics into meaningful categories. Moreover, even such a simple term as "stable" is qualitative in nature and subject to interpretation by succeeding investigators unless succinctly defined.

In this report, a **dispersion** is a mixture of oil and water which separates readily (in the order of seconds to minutes) on standing at room temperatures without the necessity for further treatment to stimulate phase segregation - an unstable mixture. The mean droplet diameter of a dispersion is greater than 100 μm, in accordance with the definition of Wasan *et al.* (1978). An **unstable emulsion** is a mixture of oil and water which requires longer settling times (in the order of minutes to hours) to achieve segregation of the phases, but which can be separated by quiescent settling, perhaps with heating. A **stable emulsion** is one which requires very long times (days to years) to separate to a significant degree. Both stable and unstable emulsions will have droplet diameters in the range of $100\,\mu m \leq d_p \leq 0.1\mu m$, again in accordance with, among others, Wasan *et al.* (1978). Finally, a microemulsion is one which has a mean droplet diameter of less than 0.1 μm, following the definition set out by Prince (1977), and is optically translucent or even transparent. More precise

differentiation between emulsions - in terms of the global separation rate constant - is discussed in Section 2.

SECTION 2

CRITERIA FOR EMULSION BREAKING

2.1 Distinguishing Among Methods

The primary distinction among techniques is based on the nature of the interaction with either of the phases to effect phase separation. Thus, the known methods can be categorized into:

- electrical
- mechanical, active
- mechanical, passive
- chemical, diluent
- chemical, surfactant
- combination

The manner in which the techniques classed under each of these categories acts on the emulsion is explainable in terms of the rate of separation of phases. Dispersed phase droplets must migrate through the continuous phase to a bulk phase boundary and coalesce with the bulk phase in order to achieve a separation. Stokes' law, which relates the terminal velocity of a solid sphere in an infinite medium (unhindered settling) to the physical parameters of the system, is often used to describe the rate of migration.

Whether this relationship is truly applicable for any but systems of low dispersed phase concentration is questionable. Moreover, at the sub-micron scale, Brownian interaction hinders the rate of progression of a droplet. Nevertheless, the analogy is useful in a qualitative sense. Stokes' law, then, is:

$$u_t = \frac{a_e \, d_p^2 \, (\rho_d - \rho_c)}{18 \, \mu_c} \qquad (1)$$

where u_t represents the terminal settling velocity of a dispersed-phase droplet through the continuous phase toward the bulk phase boundary.

Two classes of methods affect the principally the first term on the right-hand side of the equation - the effective acceleration of the droplet, a_e. Under normal gravity settling, the acceleration is g - the gravitational constant. In some active mechanical separators (centrifuges, cyclones), a_e becomes $\omega^2 r$, where ω is the rate of rotation and r the radius from the centreline of the device to the droplet, whereas in electrolytic emulsion breaking, the acceleration is a function of the net charge on the droplet and the (time-dependent for AC, steady for DC) voltage gradient in the emulsion. Chemical diluent methods, on the other hand, reduce the continuous phase viscosity, μ_c, to increase the settling velocity, as does heating the emulsion. Increasing the emulsion temperature above the ambient also affects the density difference, $\rho_d - \rho_c$, as do both dissolved and induced gas flotation methods.

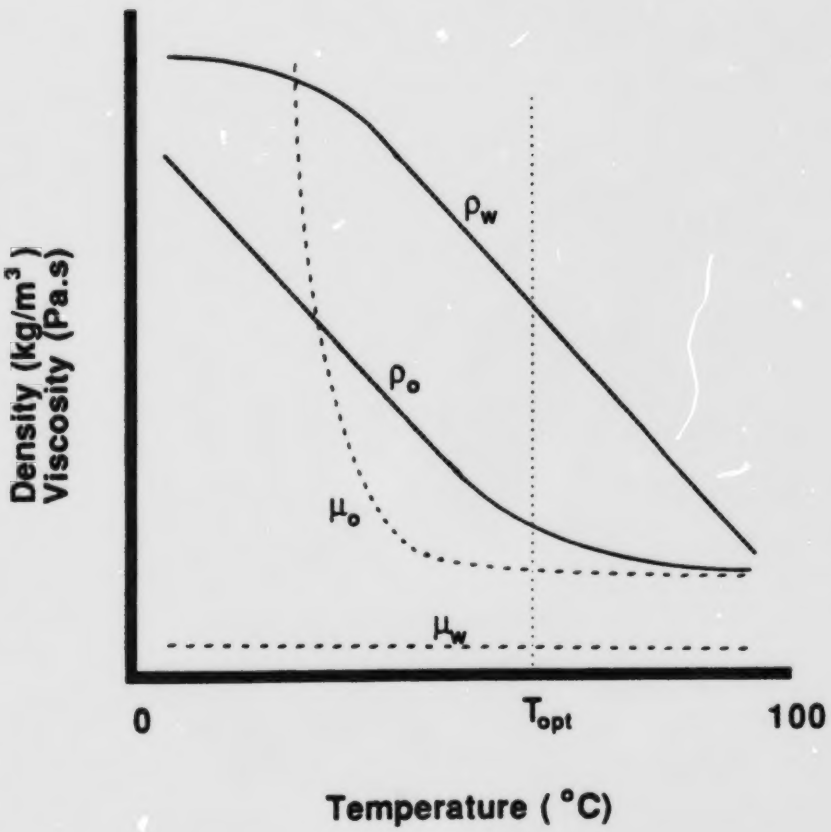
Figure 1 (p. 10) illustrates in a general manner the temperature dependence of the density and viscosity of both a crude oil and water.

By far the most effective method of accelerating phase separation, however, is to increase the droplet size since the terminal settling velocity is an exponential function of the droplet diameter. The remainder of the methods - passive (bed coalescers) and some active mechanical (conveyor, drum coalescers) methods as well as chemical surfactant methods - act to coalesce droplets in the emulsion in order to increase the mean droplet diameter.

The passive mechanical group of coalescing processes - those processes dependent on interaction of a bed, screen, or mat of materials to coalesce droplets of the dispersed phase in order to accelerate phase separation - are the primary group of interest in this investigation. In all of these processes, the feed emulsion is brought into contact with solid material(s) which interact with either or both of the phases, dependent on the surface properties of the solid. This does not preclude use of other techniques in combination with these processes; heating and diluent addition to reduce continuous phase viscosity, surfactant addition to increase the interfacial tension and enhance the droplet coalescence rate. However, the primary intent of this investigation is to evaluate the effectiveness of passive mechanical techniques with real produced fluids.

Practically every possible permutation of the techniques listed above has

FIGURE 1: Generalized Temperature Dependent Behaviour of Crude Oil and Water Density and Viscosity over the Range 0 to 100°C.



been patented at some point in time. Other investigators have considered these in detail. In particular, Siddiqi (1984) reviewed conventional commercial methods for treating produced emulsions in a study for Energy, Mines and Resources Canada. Passive methods, apart from gravity settling, were considered only in passing in that study, whereas electrolytic, active mechanical, and distillation methods were given much more detailed consideration. Hence, that study can be considered complementary to this one.

2.2 Phase Separation

The separation of a stable emulsion must be considered as a two-step process: segregation of phases (commonly termed "creaming") and coalescence of the dispersed phase droplets with the bulk phase at the interphase boundary (the interface). The initial state of the emulsion can in general be considered to be a macroscopically uniform distribution (spatially) of the phases. All of the techniques discussed in the foregoing section - with the possible exception of the chemical surfactant methods - act to induce anisotropy in that distribution; *i.e.* to impel migration toward the interface. The relative rates of the two processes are not necessarily equivalent, depending on the properties of the droplet surface. If the rate of coalescence is at least equal to the rate of migration of dispersed phase to the interface, no

"creaming" occurs and the bulk phases are separated by a thin boundary only. If, however, the discrete droplets persist after migration to the boundary (*i.e.* the rate of coalescence is less than the rate of migration), a thick interfacial "creamed" layer appears. This may persist for lengthy periods of time - months, or even years (Blair, 1960) - without coalescence of the congregated droplets.

The global phase separation rate, by analogy with heterogeneous chemical reaction, is determined by the slower of these two processes - the rate-limiting step. Many investigators (Behie *et al.*, 1983; Wasan *et al.*, 1980; Spielman and Su, 1977) describe the overall rate of coalescence of an emulsion in a settling vessel with a first-order expression:

$$\frac{dN}{dt} = -k_1 N \tag{2}$$

or, in integrated form:

$$N = N_o e^{-k_1 t} \tag{3}$$

where k_1, the first-order overall (or global) coalescence rate constant, has units of inverse time. An unstable emulsion - one in which the phases segregate quite readily - will have a rate constant in the order of 0.1 h^{-1} and larger, whereas a stable or "tight" emulsion will have a rate constant of 0.001 h^{-1} and smaller (Behie *et al.*, 1983). This seems to be a much more logical

definition of stability (in terms of the actual phenomenon of interest, *viz*: phase separation) of an emulsion than other characteristics which certainly impact on the stability (such as dispersed phase droplet diameter, interfacial shear viscosity, *etc.*) but do not describe the physical system in its entirety and so are much less definitive.

The rate of coalescence at the bulk phase boundary is determined by the nature of the droplet surface. It is well known that asphaltenes, which are omnipresent in heavy crudes and bitumens, stabilize the droplet surface (Bridie *et al.*, 1980; MacKay *et al.*, 1973; Reisberg and Doscher, 1956). It is also well established that produced fines and clays also serve to inhibit coalescence by stabilization of the droplet boundary (Blair, 1960; Mumford and Thomas, 1972).

There are, therefore, a number of principle characteristics of an emulsion which must be taken into consideration in evaluating the efficacy of a given separation technique. Among these (together with the means to deal with them) are:

- clays and fines (surfactant)
- asphaltenes (surfactant, solvent)
- continuous phase viscosity (heating, dilution)
- density difference (heating, dilution, density alteration)
- droplet size (coalescence)

The techniques discussed in the following section deal principally with means of inducing droplet coalescence.

SECTION 3

PASSIVE MECHANICAL COALESCENCE

The foregoing discussion of the generalities of emulsion separation techniques has provided the background information necessary to the discussion of individual techniques and their merits and drawbacks. Passive mechanical emulsion breakers can be further sub-categorized as:

- quiescent settling
- plate coalescers
- porous beds
- granular beds
- fibrous mats

The criterion for sub-division is obvious - the solid medium with which the emulsion is brought into contact in order to stimulate coalescence of individual droplets into larger entities. These will more readily migrate to the phase partition. Each of the sub-categories is discussed in turn.

3.1 Quiescent Settling

No recent patents or publications have been issued for quiescent

settlers, as the basis for the process is fairly fundamental. Emulsion is charged to a vessel in which the superficial velocity is low. Mean fluid residence time in the vessel is in the order of minutes to hours. The emulsion may be heated and/or diluted and/or have demulsifier added in order to accelerate the phase separation. Siddiqi (1984) described at least four recognized types of quiescent settlers: gun-barrel, settling tank, skim tank, and free-water knockout (FWKO).

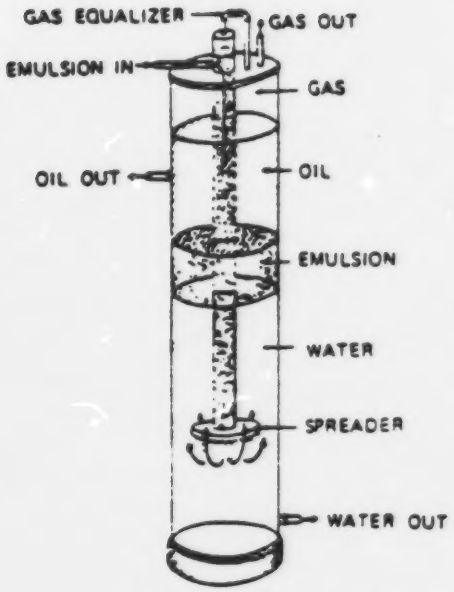
The primary merit of settling tanks is simplicity of design. The phases are allowed to separate - if they will do so at all - with a minimum of agitation and consequential hindrance of droplet migration to the phase interface. At least one recent innovation in the literature (Corti *et al.*, 1984) purportedly accelerates phase separation in heavy oil emulsions by agitation of the phases with an arrangement of buckets about the periphery of a rotating drum to which the emulsion is charged. It is suggested that this agitation "increases opportunities for particle contact and coalescence". Notably, two stages of separation and a water treatment stage are required downstream of this rotating drum coalescer.

Patents concerning quiescent (gravitational) separators are summarized in Table 1 (p. 17). A gun-barrel type settling tank is shown in Figure 2 (p. 18).

TABLE 1: Recent Patents - Quiescent Settlers

Country	Patent No.	Date Granted	Assignee	Detail
CAN	1062175	1979-09-11	Pielkenrood-Vinitex B.V., NL	Vertical tube(s), perhaps helical or connected in series by S-bends, perhaps with corrugated walls. Tubes may be annular. Flowrate controlled in range.
USA	4174751	1979-11-20	Occidental Oil Shale Inc., USA	Gravity settling at elevated temperature (> 120°F) and localized overheating.
USA	4109718	1978-08-29	Occidental Oil Shale Inc., USA	Settling in a large tank for at least 24 hours at elevated temperature (> 120°F).

FIGURE 2: A "Gun-Barrel" Quiescent Gravitational Settling Tank



3.2 Plate Media

Plate separators normally consist of a stack of parallel plates separated by a distance of a few centimetres and either aligned with or set at some angle (< 90°) to the initial direction of flow. Typically, the plate stack is tilted at some angle to the horizontal. This enables the separated light phase to migrate along the underside of the plate in the direction of bulk flow toward the upper exit of the plate stack while simultaneously permitting drainage of accumulated solids and sludge toward the lower end.

Plate separators act on an emulsion to affect separation in two ways. First, the plate material will be preferentially wet by one or the other of the phases and act as a coalescence surface. For the tilted plate interceptor/separators described above, this effect will normally be quite minor since the specific surface area (ratio of surface area to separator volume) is quite small. A recent innovation, described below, is not subject to this constraint, however. The second effect is to divide the separator volume into much smaller regions, so as to reduce the distance a droplet must travel to migrate to the bulk interface and, consequently, the overall settling time.

Bradley (1985) reviewed the field of plate separators, discussing the various types in some detail: parallel plate interceptors, tilted plate interceptors, corrugated plate interceptors. The principal application for this type of separator (Iggleden, 1978) is in the scavenging of relatively small (<

1000 ppm) amounts of light oils (API > 35) from refinery and plant-site waste and run-off streams, where long-term, low cost operation is a priority. Superior (in terms of volumetric efficiency) to the traditional API separator for these applications, neither of these devices is apparently suitable for effective separation of emulsions (Bradley, 1980).

A recent innovation in plate-type devices, however, is apparently quite well suited for resolution of crude-oil emulsions (anon., 1984). This plate medium, trademarked Performax (C-E Natco), apparently consists of a matrix of plates which serve to increase the effective contact area. Coalescence of droplets is indicated to occur on the surfaces of the plates. The medium is reportedly effective for either O/W or W/O type emulsions, which implies the use of mixed media in plate form (although the composition and configuration are proprietary - see also the discussion of mixed media in Section 3.6, below). Two field tests are described, but the only details given concerning the emulsions treated are the produced water-oil ratios (WOR's).

Design of plate-type separators is virtually always based on a simple comparison of the Stokes' law-based (Eq. 1) settling time with the residence time of the the fluid in the separator, based on the throughput. The settling velocity is based on a cut-off particle diameter. Fluid residence time is held to some multiple of the theoretical settling time to allow for a significant margin of safety,

Patents concerning plate-type separators are summarized in Table 2 (p. 22). Figure 3 (p. 24) illustrates a classical tilted plate interceptor (TPI) and Figure 4 (p. 25) shows a typical installation with the Natco PERFORMAX plate.

3.3 Porous Media

Porous coalescers rely on passage of the emulsion through a porous medium in some appropriate form (disc, cartridge, *etc.*). The medium material is selected for its preferential affinity for one of the phases of the emulsion, preferably the dispersed phase.

Processes utilizing porous materials to coalesce emulsions are operated either cyclically or in continuous fashion, and the method of operation determines the manner in which the porous material acts to effect phase segregation. In cyclic operation, the porous bed absorbs the dispersed phase material to the point where the material becomes saturated. The coalesced phase is then later recovered during the regeneration step of the cycle. In continuous operation, the bed becomes saturated with the dispersed phase and with continued operation, the coalesced dispersed-phase material exits the downstream face of the porous bed in the form of macroscopic droplets which then segregate more easily and rapidly from the continuous phase. Figure 5 (p. 27) shows a cross-sectional view of a periodically-regenerable

TABLE 2: Recent Patents - Plate Coalescers

Country	Patent No.	Date Granted	Assignee	Detail
CAN	1149756	1983-07-12	Fram Europe Ltd., UK	Parallel corrugated plates (plastic or other material), perhaps coated with silicone, with flow transverse to corrugations.
CAN	923826	1968-01-30	Combustion Engineering Inc., USA	Coalescing pack of filter media set at an angle to the horizontal for separation of oil-well emulsions.
USA	4643834	1987-02-17	Filter Plate Co., USA	Laminar flowing emulsion directed through separator with 4 stacks of V-plates horizontally spaced with 0.5 in. gap between stacks.
USA	4364833	1982-12-21	Conoco Inc., USA	Vertical separator with flow horizontally through 2 sets of vertically aligned plates set at a right angle to each other.
USA	4072614	1978-02-07	F.N. Harris, USA	Vertically stacked, high angle conic disc plates.
GB	2002248	1979-02-21	Imperial Chemical Industries Ltd., UK	Rectangular coalescing plates, reversible for backwash cleaning.
GB	1490207	1977-10-26	Shell International Research Maatsch., NL	Separator with oil coalescer plates arranged in herringbone array in a baffled, elongate tank.

TABLE 2 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
SU	1237637	1986-06-15	Brest Construction Engineering. Inst., SU	Separator with inclined corrugated plates with strip of oleophilic coalescing mesh across lower end of plates.
SU	1028345	1983-07-15	Polyak M.L., SU	"Organic glass" plate elements of fluoroplastic or organic glass [presumably acrylic] which form channels through which dispersion is directed.
SU	842030	1981-06-30	Belyavskii V.I., SU	Alternating perforated and unperforated corrugated plates, separated by partitions.
NL	82-01354	1983-10-17	Emvee Holding B.V.,NL and Myland Holding B.V., NL	Coalescer and plate separator in same vessel.

FIGURE 3: Classical Tilted Plate Interceptor

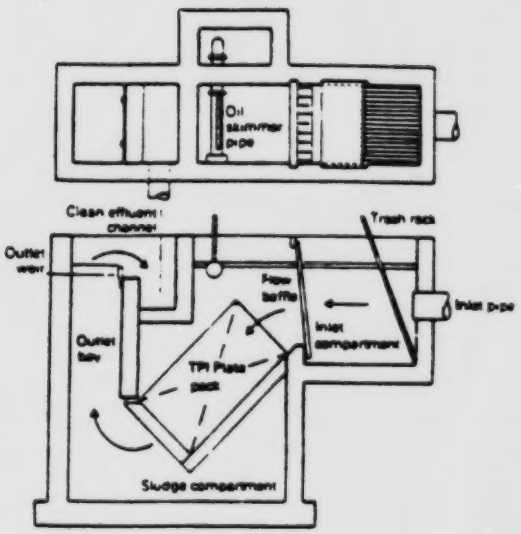
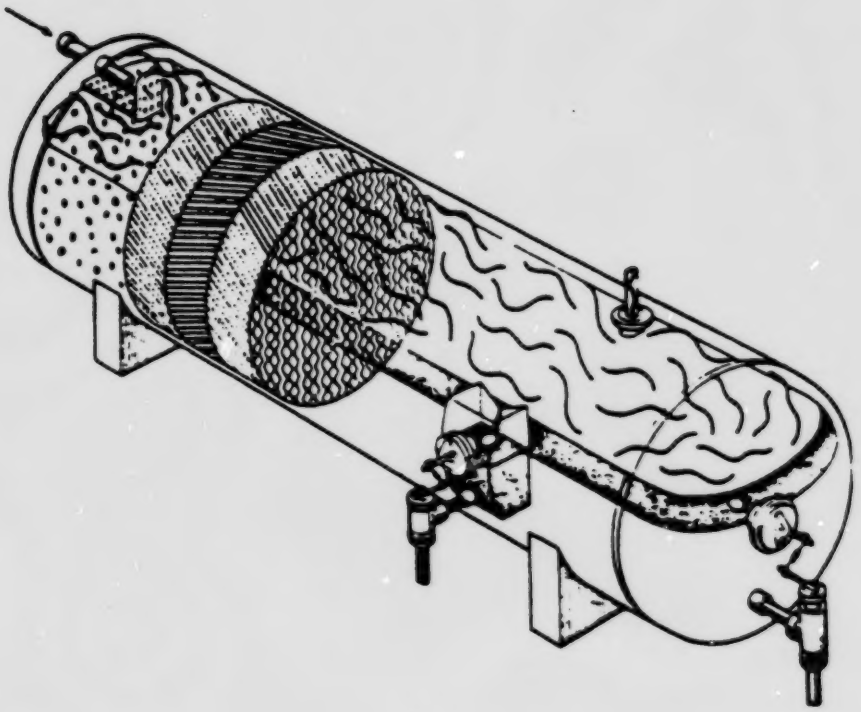


FIGURE 4: C-E Natco PERFORMAX Separator



coalescer utilizing a compressible porous medium.

Bradley (1985) discussed porous media coalescers under the name of "fixed media". A material typically used in this type of coalescer is polyurethane foam, for which material a number of patents are extant (Table 3, p. 28). Design superficial velocities to 0.027 m^3/m^2s are quoted. Potential problems can be expected where waxy crudes or crudes containing entrained solids fines are treated, necessitating frequent cleaning or regeneration of the medium.

Other, incompressible media have also been considered. Johnson (1980) examined fritted discs of aluminum-oxide, porous ceramic, and high-density polyethylene (mean pore diameters of 40, 5, and 10 μm, respectively) in coalescing Freon emulsified in water. Polyethylene, which is oleophilic, gave excellent performance. The other two media - both hydrophilic - gave only fair coalescing performance. These latter tests were with a fairly idealized system: clean fluids (filtered through a 25-μm filter), large density difference between phases (560 kg/m^3).

There are few set criteria for design of such coalescers. Johnson (1980) considered only the settling problem - downstream of the coalescer proper - from a theoretical standpoint. Laboratory experiments and field experience are otherwise suggested as design guides (Bradley, 1985).

FIGURE 5: Compressibly-Regenerable Porous Medium Coalescer

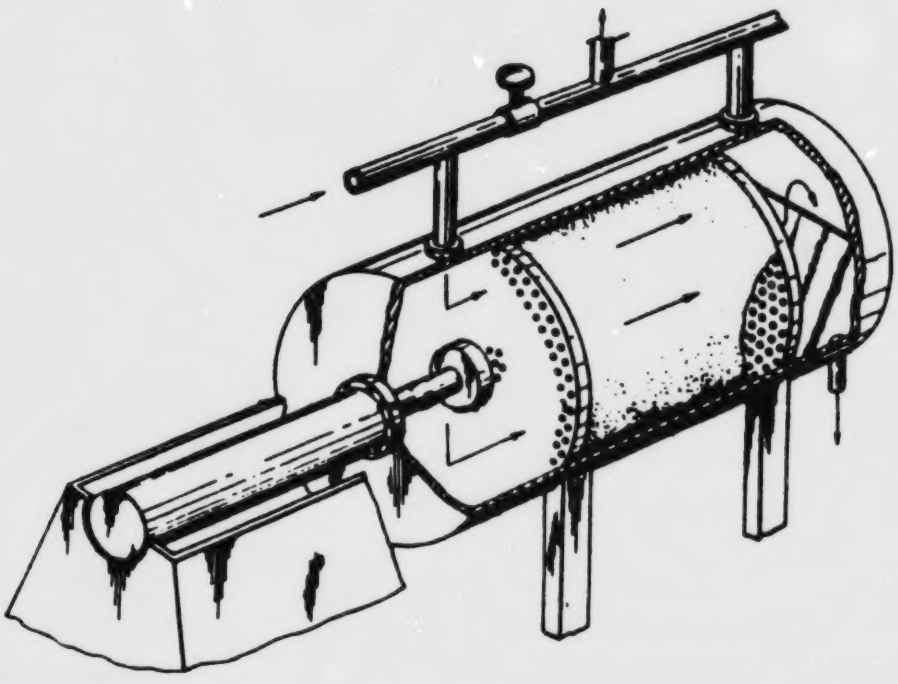


TABLE 3: Recent Patents - Porous Pad Coalescers

Country	Patent No.	Date Granted	Assignee	Detail
CAN	1136058	1982-11-23	Marine Construction and Design Co., USA	Open-pore flexible filter of visco-elastic foam, perhaps with progressivly reduced pore size toward the effluent side, compressible with a sliding piston to force out coalesced oil and filtered solids, in a cylindrical pressure vessel.
CAN	1056734	1979-06-19	Hydronautics Inc., USA	Axially-compressible porous filter disc of polyurethane foam surrounded by impervious, flexible cylinder of rubber coated fabric material, compressible by piton to force out coalesced oil.
CAN	1013268	1977-07-05	Hydronautics Inc., USA	oil absorbing, porous polyurethane foam with 30 to 100 pores/lineal in. compressed to expel absorbed oil and gravity settling of expressed liquids.
CAN	1002886	1977-01-04	Continental Oil Co., USA	dispersion (trace - 10,000 ppm oil) passed through bed of permeable polyurethane foam of 12.8 to 120.1 kg/m^3 density, 0.089 to 0.305 m thickness, at temperatures of 0 to 100°C and "flowrates" of 86 to 1711 m^3/m^2.
USA	4220544	1980-09-02	Marine Construction Design Co., USA	Rotary drum with surface of open-pore, hydrophobic, oleopilic foam material.

TABLE 3 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
USA	3779908	1973-12-18	Continental Oil Co., USA	Coalescing of dispersion "oleophilic liquid" and water by passing through permeable, non-fibrous, consolidated bed of polyurethane foam.
GB	1485623	1977	Foseco International Ltd., UK	Coalescer of reticular foam-structured ceramic material with pores progressivly increasing in size from entrance to exit, also with layer of fibrous material on inlet face.
GB	1485622	1977	Foseco International Ltd., UK	Layer with randomly-oriented aluminosilicate fibres on a porous support substrate of cellular ceramic material having porosity of continuous communication.
GB	1433764	1976-04-28	Hydronautics Inc., USA	Oil absorbing and coalescing material (polyurethane) for separation of oil from water.
GB	1418806	1975-12-24	Continental Oil Co., USA	Coalescing dispersion of oil and water by passing through a layer of polyurethane foam, previously saturated with liquid hydrocarbon, at "flowrates" of 86 to 1711 m^3/m^2.

TABLE 3 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
WGR	2303633	1973-09-27	Continental Oil Co., USA	Separation of dispersion by passing through permeable, flexible polyurethane foam, 13 to 120 kg/m^3 density, at "flowrates" of 86 to 1711 m^3/m^2.
EGR	206907	1984-02-08	VEB Pch. Schwedt, DDR	water i diesel removed by passing through ceramic filtering stones, of 30 to 80 μm pore diameter, at 0.3 to 1.0 MPa and 0 to 100°C with 3:1 N_2 to diesel and 24 hours settling, for water removal.

3.4 Granular Media

Of the media in consideration here, granular media are the least consolidated - the most porous. This has both significant advantages and disadvantages where treatment of dirty emulsions is concerned. However, the generally low cost and ready availability of the media have maintained interest in granular bed separators over the years (Odell, 1923; Bradley, 1985).

Such a coalescer essentially consists of a supported and (usually, but not not always) confined bed of granular solids. Bed materials are selected to match either the dispersed or continuous phase; *i.e.* there are examples in the literature with either type of emulsion (O/W; W/O) in which the material has been selected to be either hydrophilic or oleophilic. Indeed, there have been reports of obtaining the best coalescence performance with materials having a relatively neutral (intermediate) wettability.

Bradley (1985) termed this type of coalescing method a "loose media coalescer", describing the bed as "sand-like material" and discussing the permutations of physical arrangements which can be made (upflow, downflow, lateral flow in deep, shallow beds, combined types, *etc.*). He also discussed operation of such beds with solid fines in the feed stream and the frequency of regeneration required - which depends on whether the bed is to be operated cyclically or continuously, in the manner that porous non-rigid beds are operated.

Dow (1926), in describing the then state-of-the-art of petroleum emulsion breaking techniques, mentioned beds of diatomaceous earth (hydrophilic) or crushed glass (hydrophilic). No details were given other than the lower limit of crude oil gravity tested with such materials: 20°API.

Fowkes *et al.* (1970) used beds of dissimilar materials (mixed media) - the only record of such an attempt with granular materials in the literature. They tested binary mixtures of aluminum (20 mesh, hydrophilic), carbon (4-8 mesh, oleophilic), and iron (mesh size not specified, hydrophilic) with relatively dilute and unstable emulsions (1000 ppm water/ kerosene; 1000 ppm refinery distillate/water). Despite the idealizations, they achieved surprisingly good separations with very short residence times (5 s). They also noted that the iron in their tests tended to deplete rather rapidly, limiting the life of the bed to 10 days under certain conditions. This could be dealt with by increasing the bed volume and hence also the residence time of the fluid.

Madia *et al.* (1976) examined the effect of packing wettability on coalescer performance. Using an innovative chromatographic technique to determine the wettability of the materials, they examined anthracite coal (30-40 mesh, oleophilic), Ottawa sand (30-40 mesh, hydrophilic), polyprolylene (20-40 mesh, oleophilic), and XAD-2 (highly cross-linked styrene-divinylbenzene co-polymer; 20-50 mesh; oleophilic) in coalescing of dilute (300 - 500 ppm) O/W emulsion of Navy distillate (similar to diesel fuel) for

throughputs of 0.013 to 0.016 m^3/m^2s. They concluded that the performance of oleophilic packings is superior to that of hydrophilic packings for coalescence of O/W emulsions. Older studies (in Moses and Ng, 1985) have concluded that intermediate wettability yields the best performance, however.

Smith and Mark (1976) examined Irish peat and modified (acid-washed) Michigan peat, dried and granulated, for potential use as an oilfield emulsion coalescing medium. Testing these materials with dilute emulsions of diesel fuel in water, they determined that their performance could be as good as the XAD-2 co-polymer used by Madia *et al.* (1976).

Spielman and Su (1977) tested dilute emulsions of fairly viscous (50, 500 *cP*) silicone fluids with a specific gravity close to that of water in beds of glass beads (0.26, 0.36, and 0.50 *mm* mean diameter). These experiments were to provide experimental data for comparison with the predictions of a numerical porous bed coalescence model, and so no conclusions regarding the efficacy of a glass bead coalescing bed were drawn. An important result - pointed out later by other workers (Abdel-Ghani and Davies, 1985) - was that the depth of the granular bed beyond a certain minimum is unimportant with regard to further coalescing effect.

An innovative (and patented) design (INVERTO - Skimovex B.V.; anon., 1978) flows the emulsion to be treated through two granular beds in series. Flow through the first bed is in upflow at high superficial velocities so that the

bed becomes fluidized. The effluent from that bed is then sent through a solids trap and into the second bed in downflow, so that solids are filtered from the stream and trapped between the two beds. When the pressure drop in the forward direction becomes excessive, flow is reversed through both beds to continue normal operation uninterrupted. This design is illustrated in Figure 6 (p. 35).

Design of a granular bed coalescer is either solely by laboratory experiment and field experience, or by a combination of these (for selection of optimal parameters) with numerical simulation of coalescence.

Recent patents involving granular coalescing media are summarized in Table 4 (p. 36).

3.5 Fibrous Media

Fibrous media are among the oldest known (Dow, 1926; Shea, 1939; Burtis and Kirkbride, 1946) and most widely used materials for mechanically coalescing emulsions and separating dispersions of oil and water. Such media are utilized in a variety of forms, from unconsolidated beds (Burtis and Kirkbride, 1946; Hayes *et al.*, 1949) to knitted mats in thin (Bayley and Davies, 1978) and deep (Fahim and Akbar, 1984) beds to cartridges and sock filters of woven material (Stocker, 1978). The material may be oleophilic (Sareen *et*

FIGURE 6: Skimovex B.V. INVERTO Dual Bed Granular Medium Filter/Coalescer

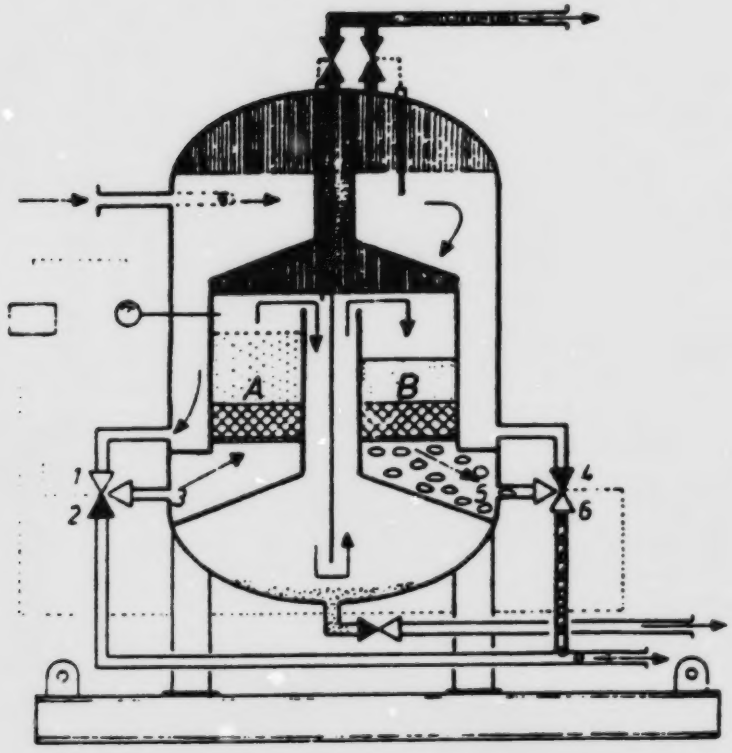


TABLE 4: Recent Patents - Granular Coalescing Media

Country	Patent No.	Date Granted	Assignee	Detail
CAN	1144498	1983-04-12	J. Kruyer, CAN	drum containing free bodies, perhaps some with oleophilic surface, and diluent , perhpas naphtha, into which dispersion of oiil and water is introduced continuously and tumbled.
CAN	1140885	1983-02-08	Cities Service Co., USA	Mixing O/W emulsion (5 to 30 vol% oil) with slurry of gypsum (1.5 to 3 kg/m^3) or by passing through a fixed bed of gypsum particles ($0.1 \leq LHSV \leq 10$).
CAN	990218	1976-06-01	Combustion Engineering Inc., USA	Bed of oil-wettable activated carbon particles, pre-saturated with hydrocarbons, to coalesce low hydrocarbon vol% dispersions.
CAN	970287	1971-10-16	Pan American Petroleum Ltd., CAN	Contacting oil-water dispersion with a bed of sulfur granules and gravity settling of the effluent.
CAN	789510	1968-07-09	Shell Oil Co., USA	Contacting suspension with a bed of solid particles. Particles of one material electrolytically deposited on a second material and surface partially abraded to expose the second material as well.

TABLE 4 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
CAN	773522	1967-12-12	Shell Oil Co., USA	Contacting suspension with a bed of solid particles. Particles of one material impregnated with a second.
USA	4251369	1981-02-17	Conoco Inc., USA	Dispersion flowed inwardly through annular cylinder of granular coalescing medium into inner vertical cylindrical settling chamber.
USA	3992291	1976-11-16	Hydromation Filter Co., USA	O/W dispersion flowed through deep bed of granulated black walnut shells.
USA	3992290	1976-11-16	Liquid Processing Systems Inc., USA	Coalescing oil from O/W dispersion by flowing dispersion through bed of brominated mono-olefin polymer resin granules.
USA	3800944	1974-04-02	Continental Oil Co., USA	Coalescing dispersion of "oleophilic liquid by passing through a bed of ion-exchange resin particles.
USA	3445399	1969-05-20	Standard Oil of Indiana, USA	Coalescing aqueous caustic in a hydrocarbon stream by passing through a bed of silica sand (0.1 to 0.6 Krumbein roundness; ASTM #10 to #100 sieves).

TABLE 4 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
GB	2052285	1981-01-28	British Petroleum Co., UK	Coalescer with a permeable wall of metal gauze enclosing particulate or fibre coalescing medium.
WGR	2303620	1972-05-24	Continental Oil Co., USA	Coalescing dispersion of "oleophilic liquid" in water by contact with Dowex 1-X8 ion-exchange resins (20/50 mesh) or sodium sulfonate ion exchange resin or quaternary ammonium chloride ion echange resin at 15.9 $m^3/h/m^2$
EGR	156166	1982-08-04	R. Kinder, DDR	De-oiling of hot water by upward flow through a bed of hydrophobic, partly coked xylitol particles at 145°C and 0.6 MPa.
SU	1230620	1986-05-15	Petlevanyii I.G., USSR	Rotary separator with a finned interior surface and filled with granular coalescing material of two types: oleophilic ($\rho > 1000\ kg/m^3$) and hydrophilic ($\rho_{HC} \leq \rho \leq 1000\ kg/m^3$).
SU	1212463	1986-02-23	Sevast Instrument, USSR	Filter element made of rotatable fibres and separator filled with granulated coalescing filler.
SU	1103879	1984-07-23	Petlevanyii I.G., USSR	Separator witha central chamber and 2 annular chambers containing granular coalescing material.

TABLE 4 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
NL	75-04951	1975-10-28	Liquid Processing Systems Inc., USA	Brominated polyethylene used to coalesce O/W dispersions.
NL	73-12706	1974-04-11	Alfa-Laval B.V., NL	Bed of plastic particles (0.5 to 3 *mm* diameter, $\rho \geq \rho_{emul}$) preferentially wetted by the dispersed phase used to coalesce O/W emulsion.
BE	890588	1982-04-01	British Petroleum Co. Ltd., UK	De-oiling of steam condensate by passing it through a coalescing cartridge and into a bed of activated carbon granules.

al., 1966), hydrophilic (Bitten and Fochtman, 1971), or mixed (Davies *et al.*, 1972).

Despite the length of time such media have been in use, however, the mechanisms of coalescence in a fibrous bed are only now becoming well understood, and this understanding has led to significant new improvements in the design of the media. Fibrous media, because of both their high specific surface area and porosity, are the best of the mechanical treating materials from the standpoint of droplet coalescing ability alone. However, fibrous media also tend to mat and plug fairly readily in dirty fluid service, requiring frequent regeneration or change-out. This is a significant drawback in comparison with plated and granular media.

Abdel-Ghani and Davies (1985) investigated the effects of fibre properties, fibre diameter, free volume, free area to flow, and fibre diameter variation on separation efficiency in fibrous mat coalescers using a numerical computer model. Simulation of fibrous mat coalescence of the kerosene-water system gave qualitatively realistic results for both dynamic (initial, time-dependent) and steady-state filtration. Predictions were not compared to experimental data, however, so the value of this model in assisting in the design of a fibrous bed coalescer is as yet open to question.

Bradley (1985) considered these media only in the cartridge (cylindrical) form and of oleophilic materials. Design throughputs he quoted were low

(0.00043 m^3/m^2s). In contrast with the other media he examined, however, Bradley used the true cartridge surface area and not the apparent cross-sectional area to flow to compute the medium capacity. The high specific surface area of these materials results in a very compact cartridge, so that the true design throughput is probably much higher - at least in the order of 0.006 to 0.012 m^3/m^2s.

Bayley and Davies (1978) discussed the application of mixed-media fibrous materials (mixed wettability) to the coalescence of emulsions in general (the particular advantages mixed-media materials may offer are discussed in greater detail in Section 3.6). Design throughputs ("loadings") of 0.0083 to 0.0222 m^3/m^2s are quoted. Moreover, Bayley and Davies indicate that the coalescence band at the bulk phase boundary normally does not appear with such mixed-media fibrous coalescers, indicating rapid coalescence of the aggregated droplets at the interface. Pressure drops are quite low (< 4 $cm\ H_2O$ at the maximum design throughput for a 0.076 m thick pad with 1 $mPa{\cdot}s$ continuous phase viscosity). Hose washing or steam cleaning of the mat is indicated to be periodically necessary if there is significant solids entrainment in the feed.

Bitten and Fochtman (1971) studied the effects of liquid velocity, fiber-bed density, bed thickness, and emulsion composition on W/O emulsions of JP-5 jet fuel and tap water. They used a 0.05 m diameter bed of fiberglass

(hydrophilic; fiber diameter: 1 - 2 μm, bed thickness: 0.01 - 0.02 m, bed density: 96 - 225 kg/m^3). Interestingly, they also included a layer of oleophilic material (knit cotton cloth) at the downstream face of the fiberglass pad "to simulate the conditions found in commercial coalescing units". Inclusion of a layer wetted by the continuous face on the downstream face of the fiber pad is a recommendation which has also been made by other investigators (Hazlett, 1969; Langdon and Wasan, 1971). As predicted by other workers (Abdel-Ghani and Davies, 1985; Sherony *et al.*, 1978), the dispersed phase saturation they measured dropped sharply from a maximum at the entrance to the bed to an asymptotic value toward the bed exit, indicating that bed thickness is not a important design parameter beyond a certain minimum value.

Burtis and Kirkbride (1946) published one of the first known studies of a fibrous coalescing bed made of other than natural materials. They examined the efficiency of beds of fiberglass (hydrophilic; fibre diameter: 7 μm, bed thickness: 0.32 m, bed density: 208 kg/m^3) in resolving W/O emulsions of brine and crude oil (gravity: 29.2 - 34.4 °API). Their throughputs ranged from 0.001 to 0.005 $m^3/m^2 s$, which is considered fairly conservative by today's standards. With these rates, they found that a bed thickness of 0.01 m was adequate to accomplish the desired separation.

Davies *et al.* (1972) investigated the so-called "junction effect" (see

discussion of mixed media, below) in a glass column (hydrophilic), the walls of which were partly coated with dimethyldichlorosilane (oleophilic). Separation of dispersions of kerosene in water was examined at the junction between the two materials. Further, they experimented with high-voidage regular woven matrices of stainless steel (hydrophilic), polypropylene (oleophilic), and a combination of these materials. Column flooding velocities with the combined material matrix was at least 50% higher than with the better of the two homogeneous materials.

Dow (1926), in discussing oilfield emulsions and techniques for resolving them, briefly mentioned passive mechanical techniques, including the Meredith and Winters patent of 1921 on the use of beds of excelsior (fine wood shavings or hay; oleophilic), cloth filters (oleophilic) in a filter-press type construction, steel shavings (hydrophilic) and screens in separating emulsions of crude oils (of gravities down to 20°API) and water. No other details were given.

Fahim and Akbar (1984) described a set of experiments with beds of mixed-media (4:1 by volume, stainless steel to fiberglass; both hydrophilic; fibre diameter: 180 and 15 μm, respectively, bed thickness: 0.1 - 0.4 m, bed density: 105 kg/m^3) fibrous packing to resolve dilute (to 1000 ppm) emulsions of kerosene in water. Throughputs for satisfactory separation ranged from 0.003 to 0.017 $m^3/m^2 s$. Because the glass wool used was described as

oleophilic when in fact it is normally hydrophilic, it was presumably treated in some manner to alter its wettability, as has been done by other investigators (Langdon and Wasan, 1971). This was not indicated by the investigators, however.

Hays *et al.* (1949) described a continuation of the study of Burtis and Kirkbride (1946), using uncompressed beds of the same fiberglass material in a pilot scale coalescer-settler unit. Design throughput was 0.005 m^3/m^2s. WOR and pH were varied to examine their effect on the efficiency of removal of salt from the produced crude. The latter had no appreciable effect and the former's effect was mostly economic (heating cost of additional water). Long term operational tests (58 weeks, total) were conducted. Wax plugging of the fiber batt by the West Texas crude (32.5°API) at ambient conditions was mentioned, so start-up was carried out with the bed pre-soaked with kerosene and brought to the operating temperature of 93.3°C prior to introduction of the emulsion.

Hazlett (1969a, 1969b) examined fiberglass (hydrophilic) and resin-bonded fiber-glass (mixed wettability; fibre diameter: 0.4 - 11 μm) in separating water/JP-5 emulsions from both a theoretical and an experimental standpoint. An important result of this work was that surfactants have no effect on coalescing behaviour within the fibrous bed. Rather, they affect coalescing behaviour downstream of the bed at the interphase boundary.

Langdon and Wasan (1971) and Langdon *et al.* (1972) described a series of experiments for removal of trace (50 - 500 ppm) oil (35 - 42°API) contaminants in a wastewater stream with treated (oleophilic) and untreated fiberglass filter pads (hydrophilic; fibre diameter: 3.2 - 10 μm, bed thickness: 0.11 - 0.14 m, bed density: 173 kg/m^3) in a filter-press construction. Throughputs ranged from 0.001 to 0.020 $m^3/m^2 s$. A teflon-coated monel screen (100 mesh) was located downstream of the fibre pad to "separate oil". The study was intended to provide design parameters for wastewater oil scavenging units equipped with fibrous media coalescers.

Mumford and Thomas (1972) carried out a series of tests with a wide assortment of homogeneous media, large diameter wire mesh pads to evaluate their effect on the size of the aggregated layer of coalescing droplets at the interphase boundary. They tested with both O/W and W/O emulsions of kerosene or toluene and water (1:1 phase ratio), using meshes of knitted steel (hydrophilic), polypropylene, copper, polyethylene and nylon (all oleophilic, including copper). For maximum separation efficiency, they concluded that the mesh should be preferentially wetted by the dispersed phase and possess a large specific surface area.

Odell (1923), in a discussion of separation of emulsions of tars produced at high temperatures from oil and coal co-pyrolysis for synthetic natural gas (water gas), indicated that screens or coarse cloths had been used

successfully to assist in this separation, sized so as to pass particles of coke carried out with the gas stream and deposited with the tar. Mineral wool and glass wool were also mentioned in this context, but no further detail was given.

Sareen *et al.* (1966) experimented with mixed beds of cotton fibre (oleophilic) and PTFE (Teflon; oleophilic), glass (hydrophilic) or Dynel (oleophilic) for separating emulsions of water and a extensive variety of hydrocarbon liquids ranging in gravity from -42 to 45°API and in viscosity from 0.6 to 138 $mPa \cdot s$. Fibre diameters ranged from 9 to 47 μm. They tested both O/W and W/O emulsions, the latter with a maximum continuous phase viscosity of 5 $mPa \cdot s$. Throughputs ranged from 0.001 to 0.018 $m^3/m^2 s$. Unfortunately, they made only visual observations on the relative coalescing and phase separating ability of the various media. A single test in excess of 70 operating hours was carried out to determine the durability of the cotton-glass wool mixed-media bed. Bed density, fibre diameter, and fibre composition were determined to be important design variables. The mixed-media beds performed very well, but their performance was not distinguishable from that of the dispersed phase-wettable beds because of the qualitative nature of the measurements made.

Shah *et al.* (1977) considered the regeneration of fibrous bed (fiberglass, coated with isobutyl methacrylate resin; oleophilic; fibre diameter: 3.2 - 10 μm,

bed thickness: 0.057 m) coalescer/filters used in the separation of dilute kerosene and water O/W emulsions (throughput: 0.003 - 0.010 m^3/m^2s). Two methods were tried: methanol (forward) washing and steaming (direction unknown). Steam regeneration was found to be much more effective than methanol washing, restoring the fibrous pad to practically its initial coalescing ability. This coalescing unit was operated in filter mode: once kerosene began to "break through" (saturate the pad and flow through to the downstream side of the pad), emulsion feed was halted and regeneration intiated. Variation of inlet oil concentration (100 - 200 ppm kerosene) did not affect the operating "life" of the mesh pad, which indicates that the hydrocarbon migration rate through the pad is independent of the rate of coalescence within the pad. The implication is that coalescence occurs in a thin layer at the upstream face of the pad, and this is supported by the results of other investigators as well (Abdel-Ghani and Davies, 1985; Bitten and Fochtman, 1971; Sherony et al., 1978).

Sherony *et al.* (19[illegible]) [illegible] extensive review of the theory of fibrous bed coalescers, including a summary of the literature and patents to that date. American patents alone to 1967 totaled 110 directly concerning the application of specific or general coalescing media, including polyoxide-treated amine-modified thermoplastic phenol-aldehyde resins, glass-wool, permeable resins, sand, and others, to a variety of emulsions. There is no mention of the mixed-media developments of approximately a decade earlier,

however.

Spielman and Goren (1970) also reviewed the literature to that point in time, indicating the wide variety of fibrous and granular materials mentioned to that point. Some mixed-media studies were summarized, notably the work of Sareen *et al.* (1966), but not that of their contemporaries, Davies and co-workers in the U.K. Spielman and Goren (1972a, 1972b) developed a numerical model for a fibrous bed coalescer pad and described a series of experiments with glass fibre mats (fiber diameter: 3.5 - 12 μm, bed thickness: 1 - 3 mm, bed density: 560 kg/m^3) for separating emulsions of silicone fluids (500 ppm; density: 994 kg/m^3, viscosity: 44 - 465 $mPa \cdot s$) in water. Both untreated (hydrophilic) mats and mats which had been coated with silicone (oleophilic) were tested. The model developed assumed a constant dispersed phase saturation throughout the mat, which is contrary to what has been observed by other investigators. Spielman and Goren also found that the untreated (hydrophilic) mat gave superior separation of the oil, which again is contrary to what others have found.

Vinson and Churchill (1970) carried out experiments with geometrically-regular photo-etched nickel screens (both hydrophilic and oleophilic after treatment with octadecylamine; fibre diameter: 8 - 31 μm) as idealized fibrous materials to separate O/W emulsions (500 ppm cyclohexanol in water; throughput: 0.0003 - 0.021 $m^3/m^2 s$), attempting to correlate various

dimensionless groups with the observed coalescing behaviour of their micro-screens. Perhaps the most useful conclusion of this work was that, above a critical velocity, coalescence behaviour deteriorated, with passage of increasingly smaller diameter drolets of dispersed phase which affected the downstream separation rate.

Zibert and Gibkin (1985) described an experimental separator which utilized either coiled glass fibre mats (hydrophilic) or polymer rings (polyamide, polyethylene, high-density polyethylene, or polystyrene; all oleophilic) wrapped with 1 to 2 layers of cotton fabric (oleophilic) to separate diethylene glycol (DEG) from natural gas condensate (20:1 - 50:1 volume ratio, condensate:DEG). For throughputs of 0.008 to 0.012 m^3/m^2s, an improvement of DEG recovery by a factor of 8 to 10 over gravity settling alone was noted with the glass mat coalescer and a factor of 2 with the polymer ring unit.

Design of coalescers of fibrous materials is based on premises similar to those for granular materials: experimental trial-and-error, possibly combined with numerical simulation with one of the models indicated above. No other criteria are generally agreed upon, although Sareen *et al.* (1966) has attempted to set out such criteria based on the summarized results of prior studies.

Patents concerning fibrous media coalescers are summarized in Table 5

(p. 51). Figure 7 (p. 60) illustrates what a typical fibrous-pad coalescer installation might look like.

3.6 Mixed-Media Materials

Studies of mixed-media coalescers in the literature have all indicated superior performance relative to a homogenous medium wettable by either the dispersed or continuous phases. The term "mixed-media" simply implies an intimate combination of materials of similar type but differing wettability by the immiscible phases of a dispersion or emulsion. Differences in medium wettability have also been termed differences in "surface energy" (Bayley and Davies, 1978). The unusually effective coalescing ability of these materials has been attributed both to a "junction effect" (Davies *et al.*, 1972) and - perhaps more precisely - to the electrophoretic action of the potential difference (electromotive potential) between dissimilar materials in close proximity on the droplets in an emulsion (Fowkes *et al.*, 1970).

Droplets in an emulsion often carry a charge (correlatable with the zeta potential) which arises as a result of the electrical double layer developed at the droplet surface, and this charge can be used to impel dispersed phase droplets in an electrical field - the effect which is exploited in an electrolytic emulsion treater. The limiting (terminal) velocity is given by the expression (Fowkes *et al.*, 1970):

TABLE 5: Recent Patents - Fibrous Coalescers

Country	Patent No.	Date Granted	Assignee	Detail
CAN	866587	1968-11-12	Esso Research and Engineering Co., USA	Coalescer and filter employing cartridge of material.
CAN	864311	1968-08-30	Chevron Research Co., USA	Fiber filter with the fibers bonded together with a polymer resin, both materials being oleophilic.
USA	4640781	1987-02-03	Shell Oil Co., USA	Cluster of fibres with their lower end secured to a horizontal disc, which is vertically mobile, and with their upper end free in an inverted cone separator. Fluids flow upward through the fibres into the separator.
USA	4299699	1981-10-11	M.A. Boogay, USA	Cylindrical coalescer/filter of yarn-like material wound helically about a porous central core. Flow directed radially outward.
USA	4240908	1980-12-23	Mapco Inc., USA	Vertical cylinder of aluminum or stainless steel coated with vinyl, epoxy, acrylic, polypropylene, polyethylene, PVC, PTFE, or Phenolic resin oleophilic material in a single or multiple layers. O/W emulsion flow is radially outward.

TABLE 5 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
USA	4226722	1980-10-07	Amoco Production Co., USA	Oil coalescing filter cartridge of porous fibrous wool, cotton or plastic material supporting a solid phase yellow sulfur.
USA	4171264	1979-09-04	Shell Oil Co., USA	O/W emulsions (30 to 500 ppm oil) coalesced by contact with length-classified (50 to 100 μm), chemically-pulped cellulose fibres in suspension (1000 to 5000 ppm) or as fixed bed.
USA	4116935	1978-09-26	Savage Technical Services Inc., USA	Tank with foraminous oleophilic web the flow path to intercept and coalesce hydrocarbons.
USA	3980565	1976-09-14	L. Fowler, USA	Coalescing emulsion by flowing radially outward through a vertical cylindrical shell of emulsion -breaking fibrous material and through a mat of porous flexible substrate supporting copper, tin, aluminum, nickel, zinc, or alloy metal particles.
USA	3931019	1976-01-06	Products and Pollution Controls Co., USA	Emulsion breaking in radial outward flow through a cylinder of emulsion-breaking fibrous material and helically-wound wire on the exterior surface (45 to 111 N tension, 6 to 25 mm spacing).

TABLE 5 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
USA	3800945	1974-04-02	Cata-Sep Inc., USA	Coalescing an emulsion by passing it radially through a layer of polyester, acrylic, modacrylic, or fiberglass fibrous material, a layer of fiberglass screen, and a layer of polyester fibrous material supporting diatomaceous earth, asbestos, and/or silica particulate material.
USA	3743599	1973-07-03	Brunswick Corp., USA	Cylindrical coalescing filter for oil-water separation comprised of nylon yarn covered by a winding of polypropylene yarn, both impregnated with oleophilic resin. Flow is radially outward.
USA	3738492	1973-06-12	Brunswick Corp., USA	Coalescer consisting of a series of upflow vertical coalescing oleophilic filter medium-containing tanks.
USA	3450632	1969-06-17	Chevron Research Co., USA and Johnson and Johnson Inc., USA	Graded density batt of polyester, acrylic, or modacrylic medium bonded with polyacrylic, polyurethane, or synthetic rubber to coalesce and remove traces of oil from immiscible liquids.

TABLE 5 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
GB	2161395	1986-01-15	Shell International Research Maatsch., UK	Separation of oil from emulsion by contact with an axial bundle of fibers attached at the lower end to a movable disc and free at the upper end in the expanding portion of an inverted cone separator.
GB	2156233	1985-10-09	Esplen Alex and Co., UK	Chamber containing a coalescing pad of alternating layers of stainless steel and a composite fabric, partly of monofilaments and partly of staple fibres yarn.
GB	2135207	1984-08-30	Shell International Research Maatsch., UK	Separation of O/W dispersions (d_p < 10 μm, inlet oil concentration < 0.5 mol/m^3) by passing them through a coalescing layer of propylene fibres treated with organosilicon compound to remove oil.
GB	2052285	1981-01-08	British Petroleum Co., UK	Coalescer with a permeable wall of metal gauze enclosing a particulate or fibrous coalescing medium.
GB	2046115	1980-11-12	Plenty Group Ltd., UK	Coalescing medium composed of one or more layers of fibrous material (glass fibre for W/O; polypropylene or other hydrocarbon for O/W).

TABLE 5 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
GB	2020564	1979-11-21	Fram Europe Ltd., UK	Annular filter-coalescer of fine nylon mesh screen coated with a hydrophilic polysiloxane layer.
GB	2001542	1979-02-07	Imperial Chemical Industries Ltd., UK	Rectangular coalescing fibre pad, reversible for backwash cleaning.
GB	1535160	1978-12-06	J. Sakaguchi, JA	Two cylindrical coalescing filters in series with radially inward flow through the upper, radially outward flow through the lower.
GB	1445692	1976-08-11	Knitmesh Ltd., UK	Coalescing with a pervious packing of randomly and loosely-massed components.
GB	1409045	1975-08-10	Knitmesh Ltd., UK	Composite droplet coalescer packing of two materials (one of metal, metal salt, or metal oxide; one of polypropylene, PTFE, polythene, nylon, etc.).
GB	1312664	1973-04-04	Esso Research and Engineering Co., USA	O/W dispersion (60 to 291 ppm oil) is coalesced in a disc cartridge with the first layer of lipophilic resin-coated glass fibre web and the second of hydrophilic glass fibre web.

TABLE 5 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
GB	1232231	1971-05-19	Chevron Research Co., USA and Johnson and Johnson Inc., USA	Oil coalescer of poyester, acrylic, and/or modacrylic sythetic fibre batt bonded with 25 to 100 % w/w polyacrylic or polyurethane resin (5 to 20 kg/m^3 upstream, 50 to 80 kg/m^3 downstream batt density). Fluid velocities of 0.5 to 1.8 mm/s.
GB	1228563	1971-04-15	Purolater Inc., USA	Coalescer of batt of layer of resinated fiberglass and layer of unresinated fiberglass to coalesce O/W emulsions.
WGR	3502671	1986-07-31	Wyzsza Szkola Morska *et al.*, BRD	Oil is coalesced from emulsion by passage radially outward through a layer of oleophilic synthetic fibres, a layer of glass fibre (1 to 4 μm diameter), a layer of oleophilic synthetic fibre, and a layer of woven fabric, with the layers bonded by needle-felting.
WGR	2914816	1979-10-18	Shell International Research Maatsch., NL	Coalescer for liquid dispersions with a wall of fibrous polyprolpylene material
WGR	2800061	1978-07-20	National Marine Service, USA	Horizontally oriented coalescer screens for separation of oil and water.

TABLE 5 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
EGR	200978	1983-06-29	VEB Petrochem. Schwedt., DDR	Water and solid impurities (< 50 μm diameter) removal from hydrocarbon fractions by passing them through multi-layer bed: first stage of PTFE fibre (0.5 to 2.0 m long), settling section, second stage of glass wool quilt fibre (0.1 to 5 cm thick).
SU	1247035	1986-07-30	Oil Collect. Trans., USSR	Horizontal emulsion coalescer with longitudinally-oriented synthetic fibre supported by end plates, perhaps with three or more such coalescer sections included with progressivly increasing fibre density.
SU	1212463	1986-02-23	Sevast Instrument, USSR	Filter element made of rotatable fibres and separator filled with granulated coalescing filler.
SU	1165422	1985-07-07	Oil Prod. Gath. Trans., USSR	Cylindrical coalescer for emulsions with longitudinally-oriented coalescing filaments and radial blades to impel flow toward centre of tube.

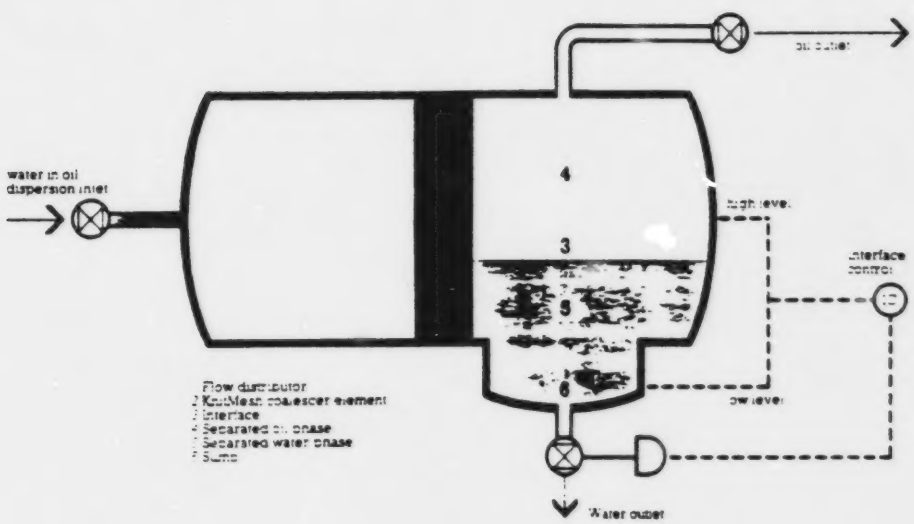
TABLE 5 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
JA	61-257212	1986-11-04	Asahi Chemical Industry Co., JA	Sheet (0.1 to 70 *mm* thick) of non-woven polyethylene terephthalate fibres (0.1 to 10 μm diameter) wrapped around a stainless steel cylindrical net, through which emulsion passes at a "flowrate" of 1000 kg/m^2.
FR	2551671	1985-03-15	Sofrance S.A., FR	Coalescer with three stages: first is of ploypropylene felt (0.5 to 2 *mm* thick) not wettable by the dispersed phase; the second is of glass wool; the third of polyacrylonitrile synthetic fibre (1 to 1.5 *cm* thick). For W/O emulsions; used ahead of principal coalescer with one or more beds of a mixture of glass and SiO_2 fibres, a layer of plastic foam, and a bed of polyacrylonitrile or polyester fibres wettable by the dispersed phase.
EP	207797	1987-01-07	British Petroleum Co. Ltd., UK	Coalescer cartridge of nylon-66 synthetic fibres (21 *cm* long, 26 μm diameter) for filtration and coalescence of solids or immiscible liquids.
EP	4724	1979-10-17	British Petroleum Co. Ltd., UK	Coalescer cartridge with two support plates and wool, cotton, or polyamide fibres secured to both plates.

TABLE 5 (continued)

Country	Patent No.	Date Granted	Assignee	Detail
EP	2524	1979-06-27	General Electric Co., USA	Coalescing matrix of randomly interspersed long oleophilic non-corrodable stainless steel or plastic fibres configured to provide a specified mean porosity along the flow path.

FIGURE 7: Typical Fibrous Medium Coalescer



$$u_t = \frac{\zeta E K}{6 \pi \mu_c} C \qquad (4)$$

where ζ is the zeta-potential (V) of a droplet of dispersed phase, E the potential gradient (V/m), K the dielectric constant (or permittivity) of the continuous phase (F/m), and C a constant which ranges from 1.0 to 1.5 and is a a function of the effective hydrodynamic radius of the droplet. Proximity of two dissimilar materials gives rise to a voltage gradient inversely proportional to the square of the distance separating them, which results in intense electrical fields with the materials in intimate contact.

This mechanism, although still somewhat speculative, potentially explains why mixed-media fibrous materials are so particularly effective (because of the large number of dissimilar material "junctions"), why mixed-media granular materials can be expected to be somewhat less so (fewer junctions, due to lower specific surface area), and why alternating layers or plates of (homogeneous) dissimilar materials will be hardly any more effective than a coalescer of similar geometry and of a homogeneous medium. Davies *et al.* (Knitmesh corp. publ.) have also pointed out that, with mixed-media coalescing materials, it is irrelevant which phase is continuous and which dispersed. Thus, phase inversion - which is well known to occur in oil recovery projects - is not a significant problem in terms of compatibility of the coalescing medium with the emulsion. Selection of the particular type and composition of mixed-media to use will therefore depend on the type of fluids

being treated, on the amounts and size range of solids to be expected with the fluids, and on levels of acceptable coalescence performance, determined on an individual, case-by-case basis.

SECTION 4
CONCLUSIONS

(1) A reasonably complete review of developments and the state-of-the-art in the area of passive mechanical coalescence of oil-water emulsions has been carried out.

(2) No scientific publication or patent has been found which has adequately addressed the excellent potential for treating emulsions of heavy oils or bitumens and water with passive mechanical coalescing methods.

(3) There is a significant gap in the body of knowledge on the application of passive mechanical coalescing methods to real oilfield emulsions and in understanding the attendant problems that such application will entail.

(4) Mixed-media, especially in fibrous or granular form, show excellent potential for accelerating the coalescence and separation of heavy oil or bitumen and water emulsions. Presently, design of emulsion coalescers is still dependent on bench-scale laboratory work and field testing to evaluate the utility and performance of any coalescing material, however.

SECTION 5

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STUDY OF MECHANICAL COALESCING FOR PETROLEUM EMULSIONS

DSS CONTRACT No. 23440-6-9146/01-SQ

TASK 2 FINAL REPORT: BENCH-SCALE EXPERIMENTAL STUDY

BY

W.Y. SVRCEK ENGINEERING LTD.

FOR

COLT ENGINEERING CORPORATION
CALGARY, ALBERTA
August 8, 1988
COLT FILE No. 88-C-447

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56 pp

MICROMEDIA

SUMMARY

Separation of the phases in stable heavy oil emulsions is a significant problems for heavy oil producers throughout Alberta. Existing means for accomplishing a good separation are typically expensive in terms of either capital or operating cost, or both. There is considerable incentive to develop a less expensive means for separating the phases. Hence, this study was undertaken to investigate a potentially promising method.

Passive mechanical methods consisting of contacting an oil dispersion with a mesh medium of mixed-wettability composition have shown great potential with other hydrocarbon-water systems. Mixed wettability composition denotes a mesh composed of fibers of at least two different types, one of which is preferentially wet by the continuous phase, the other by the dispersed phase. This not only takes advantage of the so-called "junction effect" to accelerate the coalescence of dispersed-phase droplets, but has the additional advantage of being equally capable of treating dispersions with either phase continuous - something which cannot at present be done with homogeneous-mesh coalescing media. Such mixed-composition systems have been demonstrated successfully in such applications as refinery surface run-off water clean-up and separation of kerosene-water dispersions.

To date, no prior study has been published which examines the separation of highly-stable heavy oil emulsions with mixed-composition mesh media. This test program was carried out as Task 2 of the Study of Mechanical Coalescing of Petroleum Emulsions undertaken by Colt Engineering Corporation for Energy, Mines, and Resources Canada (DSS Contract No. 23440-6-9146/01-SQ).

Highly stable water-in-oil (W/O) emulsions were created for this study, using a heavy crude of about 12°API. The degree of phase separation of such an emulsion in a bench-scale coalescing vessel and separator was measured for five commercial mixed-composition mesh and fibrous coalescing media. Separations achieved were compared with that due to conventional gravitational segregation alone. None of the media showed any improvement over the empty vessel at the test conditions of 100°C and ambient pressure. Further tests were conducted at higher temperatures (110 and 125°C) and elevated pressures with one mesh-type medium. Again, no significant enhancement in phase separation over the empty vessel was found.

It is recommended that further, more comprehensive studies be

conducted at the bench-scale to verify these results. The effects of increased separator residence time, increased fluid velocity through the coalescing medium, and emulsion phase inversion need to be considered. These variables were not examined in this initial study. Further, a simple residence time distribution test should be carried out on the coalescing vessel to ensure that fluid bypassing of the coalescing medium along the vessel walls is not significant. There is still potential for this phase separation method, because there are stones as yet unturned.

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NOTATION

$C^*_{w,t}$	volume fraction of water in emulsion at time t, based on volume of emulsion remaining at time t
$C^*_{w,0}$	initial volume fraction of water in emulsion
CB_i	component balance, %
$\bar{d}_p$	mean droplet diameter, m
k_1	first-order phase separation rate constant, h^{-1}
p_{min}	minimum operating pressure - separator, kPa
$p_{v,w}$	vapour pressure of water, kPa
$R_{w,1}$	fractional recovery of water - feed volume basis, %
$R_{w,2}$	fractional recovery of water - products volume basis, %
$R_{o,1}$	fractional recovery of oil - feed volume basis, %
$R_{o,2}$	fractional recovery of oil - products volume basis, %
T_{sep}	temperature of separator vessel contents, K
TB	total balance (product basis), %
$\bar{u}_f$	superficial feed velocity, m/s
$V_{e,t}$	volume of emulsion at time t, L
$V_{e,0}$	initial volume of emulsion, L
$V_{i,H}$	heavy-phase component volume, L

$V_{i,L}$	light-phase component volume, L
$V_{i,F}$	feed component volume, L
$V_{t,F}$	total feed volume, L
$V_{t,H}$	total heavy-phase volume, L
$V_{t,L}$	total light-phase volume, L
x_F	feed component volume fraction
x_H	heavy-phase component volume fraction
x_L	light-phase component volume fraction

SECTION 1

INTRODUCTION AND OBJECTIVES

1.1 Scope of Investigation

One of the major problems facing oil producers everywhere is the production of oil in the form of an emulsion with water. This occurs almost universally where oil and water come into intimate contact in the reservoir or the wellbore during production because of the high shear and elevated temperature conditions there. Thus, whether the field is under waterflood, is produced by cyclic steam injection and backflow, or merely produces copious amounts of formation water, emulsion production is the likely result. Emulsions of conventional, high-gravity oils and water can usually be broken (phases segregated) by conventional techniques: heating and gravitational settling. Emulsions of heavy oils, however, can be much more difficult to treat because of their stability. This stability is attributable to a number of factors, including similarity of phase densities, continuous-phase viscosity, the presence of argillaceous fines (which tend to physically stabilize droplet surfaces), and the action of components of the oil as surfactants (also stabilizing the phase interface by electro-chemical or other means). The import of all of this is that separation of water from such an emulsion is a difficult and costly process. Existing techniques for doing so are available,

including electrolytic, chemical, and distillative methods. Typically, however, these processes have high associated capital and operating costs. An enormous economic incentive exists, therefore, to effect a less-costly phase separation by novel means.

This experimental program was initiated as an initial phase of a larger research program into the effectiveness of passive mechanical media for separation of heavy oil-water emulsions. In particular, it was undertaken to obtain estimates of the relative effectiveness of such media and to provide engineering information for the design of a pilot-scale test coalescer in a later phase of the project. This program comprised Task 2 of DSS Research Contract No. 23440-6-9146/01-SQ.

In Task 1, an extensive review of prior experimental and theoretical work on passive mechanical emulsion breaking techniques and media was carried out. In particular, developments with mixed-composition knitted mesh media were examined. Such media are comprised of filaments of at least two differing materials, each having a particular affinity for (or preferentially wet by) one of the phases of the emulsion. The particular interest was in application of such materials to the coalescence of dispersed-phase droplets in emulsions of heavy oils (°API < 20) with either phase continuous.

Prior testing of such media has always been carried out with fairly readily separable systems such as kerosene-water or water with trace amounts of

conventional light oils ($\bar{d}_p > 30\ \mu m$). The ability of mixed composition media to accelerate the rate of droplet coalescence and phase separation in such systems is superior to that of homogeneous (single constituent) knitted mesh media (Stocker *et al.*, 1988). This advantage has been attributed to a so-called "junction effect" at the points of contact between filaments of the two differing materials. Moreover, because of the dualistic wettability of the mesh, emulsions of either type (oil or water continuous) could be treated with equivalent efficacy.

Reports of a program of rigourous tests with highly stable heavy oil emulsions have not been previously published, however. This study was undertaken to rectify this situation and examine the potential for the use of mixed composition knitted media for treatment of oilfield emulsions.

1.2 Program Objectives

Primary objectives for the experimental research program were established at the outset of the task. These included:

(1) Construction of a bench-scale test coalescer and separator to test commercially-available and other coalescing media.

(2) Emulsification of a heavy oil with water to produce highly stable emulsions of either type (oil or water continuous).

(3) Evaluation of the ability of the various media to coalesce and separate emulsions of either type.

(4) Examination of the effects of various operational parameters (coalescer and separator temperatures, emulsion feed rate, separator residence time) on the relative efficiencies of separation of the various media.

SECTION 2

EQUIPMENT AND PROCEDURES

2.1 Emulsion Making and Stability Testing

a. Emulsion Making

The initial problem of the experimental program was to obtain stable, reproducable emulsions of either type. The difficulty in utilizing a real oilfield emulsion is that the properties of the emulsion would change as it aged; phase separation occurs with time and the droplet size distribution and relative proportions of the phases present are altered. In order to test all the media on an equivalent basis, it was necessary to emulsify oil and water in accordance with a standardized procedure. Hence, a "recipe" for emulsification was established and tested. A 12°API oil was used; its properties are tabulated in Table 1. Temperature dependence of the density and viscosity of the oil are shown in Figures 1 and 2. Density was measured by pycnometer over the full temperature range of interest, substituting glycerine for water at temperatures above 95°C. Viscosities were measured with a Viscometers U.K. Model RV-8 concentric cylinder viscometer equipped with a heating mantle.

Table 1: Feed Emulsion Oil Component Properties

Gravity	11.9°API
Asphaltenes Content (C_5-insoluble)	13.9 wt.%
Sulphur Content	4.4 wt.%
Mean (50 wt%) Boiling Point (Simulated Distillation)	581°C
Electrical Conductivity	12.5 μ mho/cm @ 22.5°C
Colour	opaque black (dark brown in thin film)

Measured Density with Temperature

Temperature (°C)	Density (kg/m^3)
23.3	980.8
55.0	974.1
67.0	960.6
94.5	960.1
127.0	940.1
141.0	931.7

Measured Viscosity with Temperature

Temperature (°C)	Viscosity ($mPa.s$)
30.6	6530
50.0	1220
70.0	340
90.0	140
110.1	78.8
120.0	66.3
130.0	57.5
140.4	38.8
150.3	38.8

Figure 1: Water, Heavy Oil Density Temperature Dependence

COLT Mechanical Emulsion Breaking Study

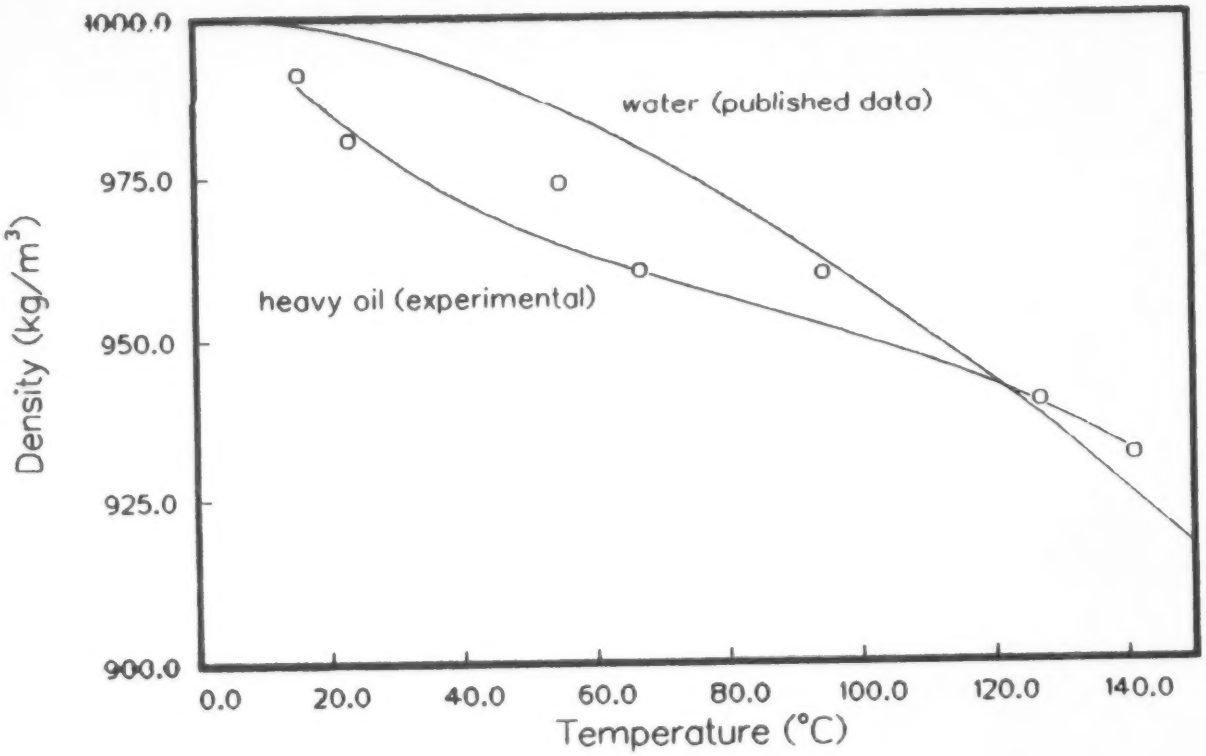
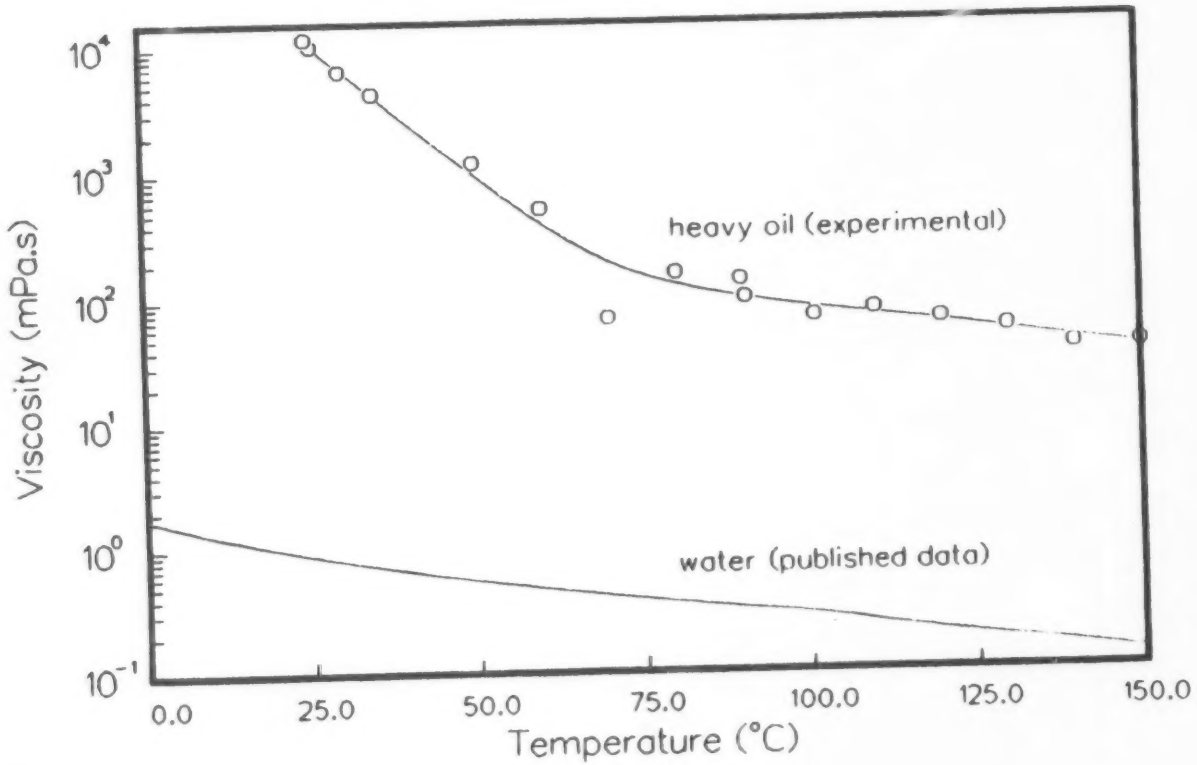


Figure 2: Water, Heavy Oil Viscosity Temperature Dependence

COLT Mechanical Emulsion Breaking Study



The procedure established for producing a 30% W/O (30% by volume water-in-oil) emulsion is as given below:

(1) Feed oil maintained - pre-heated - at 75 to 80°C.

(2) add 39 g salt (NaCl) and 71 g detergent (generic) per L total emulsion to mixing container.

(3) add 0.3 L 40°C water per L total emulsion to mixing container.

(4) stir briefly to dissolve salt and detergent in water.

(5) add 0.7 L 75°C oil to mixing container.

(6) emulsify with motor-driven agitator (hand-held 2600 rpm electric drill with 2.5 cm dia. paint mixer) for 10 min.

(7) pour emulsion into test loop feed drum.

(8) heat emulsion and circulate through feed pump and recycle loop to preheat feed lines and condition emulsion until emulsion temperature reaches 75°C.

(9) re-emulsify with motor-driven agitator at 2600 rpm for 5 min.

b. Emulsion Stability Testing

In order to evaluate the stability of the emulsions thus created, a second test procedure was devised to measure the volumetric phase separation rate. A glass graduated cylinder containing 60 mL of freshly prepared emulsion was placed in a heated water bath with transparent walls. A strong light was directed at the cylinder from behind. The volume of water separated from the emulsion was measured with time, and the volumetric rate of separation was correlated with a rate equation. The value of the rate constant is dependent on the stability of the emulsion. Such a procedure has been used previously to characterize emulsion stability (Wasan *et al.*, 1978).

2.2 Bench-Top Coalescing Test Facility Description

A bench-top coalescing test loop was built to evaluate the relative ability of the media to accelerate emulsion droplet coalescence and phase segregation. The major components of the test loop were:

(1) feed drum, drum heaters, and power controller

(2) emulsion feed pump, motor, and speed control

(3) line heater and power controller

(4) coalescer, heater, and power contoller

(5) oil-water separator, heater and power controller, heavy-phase liquid level sensor, solenoid-actuated dump valve, and valve controller

(6) light- and heavy-product stream chillers

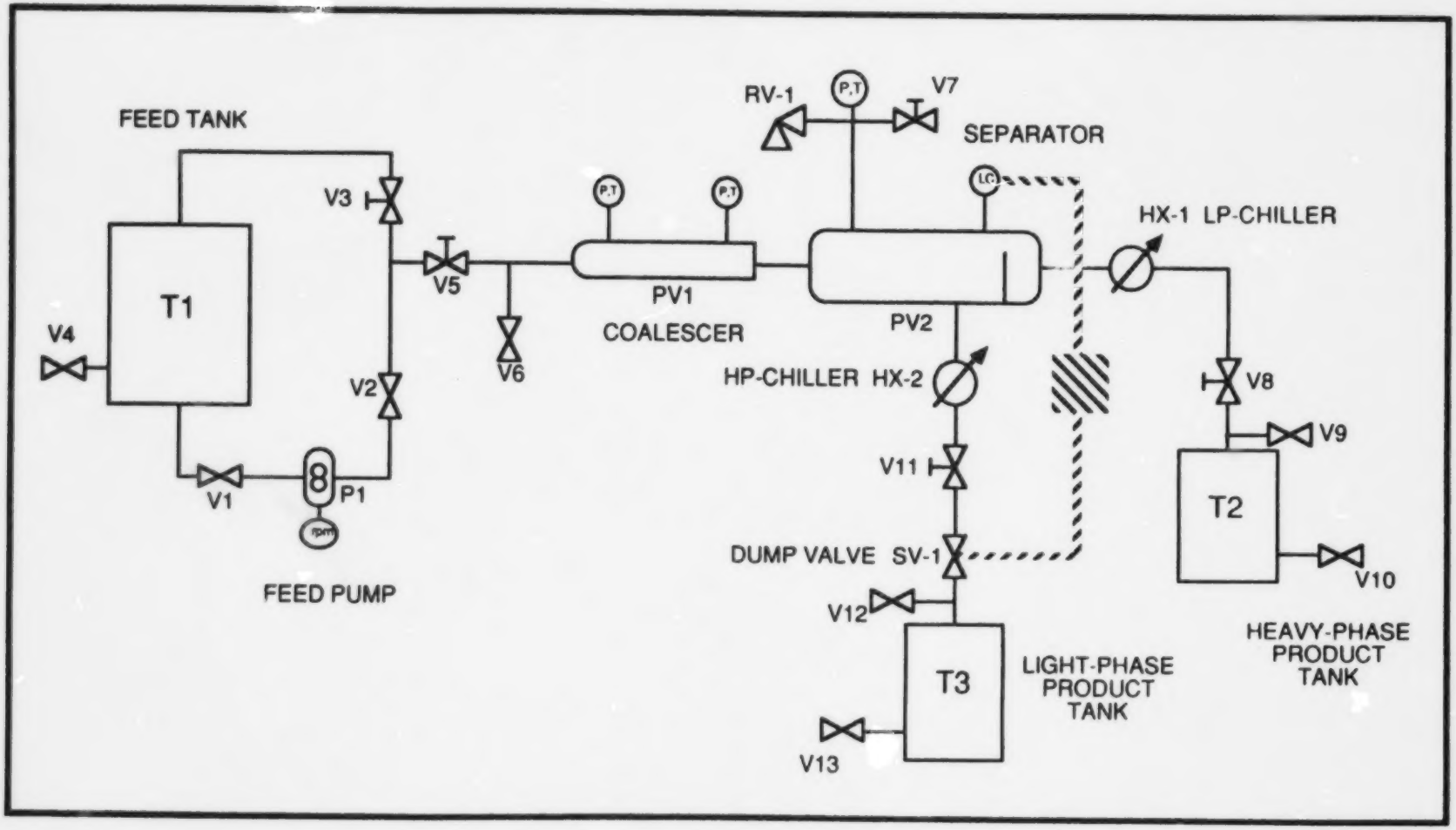
(7) product collection tanks

The test loop as it was built is illustrated in Fig. 3. Views of the bench-top assembly at table-top level are given in Plate 1 - with heater power controllers, feed drum, feed pump and variable speed drive in the foreground - and in Plate 2 - with separator, instrumentation, and product receiver drums in the foreground (experimenter shown for scale). A plan view illustrating the component layout of the test loop is shown in Plate 3. The feed drum is at the lower-left corner of the picture, the feed pump and drive at the left, and the coalescer is the long, thin vessel to the upper left. In the upper-right corner is the separator - the thicker, insulated vessel - with the product chillers just below between the separator and the instrumentation package. The light and heavy product receiver drums protrude from beneath the table at the center of the photograph.

a. Emulsion Feed System

Feed and product receiver drums were open-top 25 L pails. The feed drum was heated with a pair of 2.5 m × 2.5 cm heavily-insulated heating tapes

Figure 3: Test Loop Schematic Flow Diagram



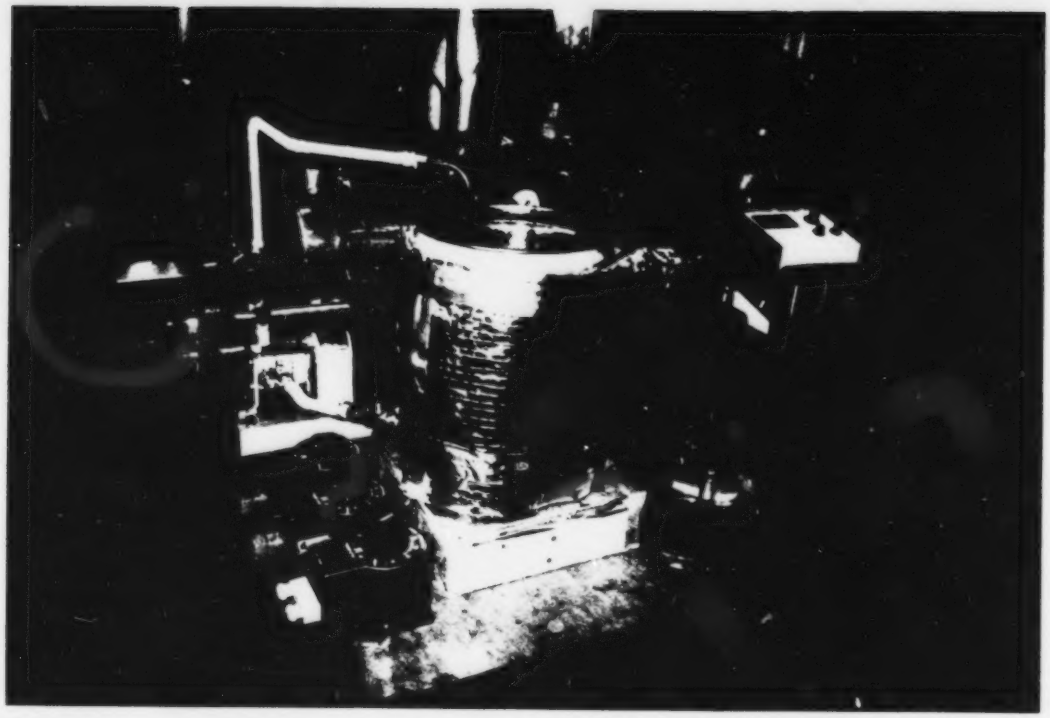


Plate 1: Bench-Top Experimental Coalescer Assembly (Oblique View - Left)

Plate 2: Bench-Top Experimental Coalescer Assembly (Oblique View - Right)

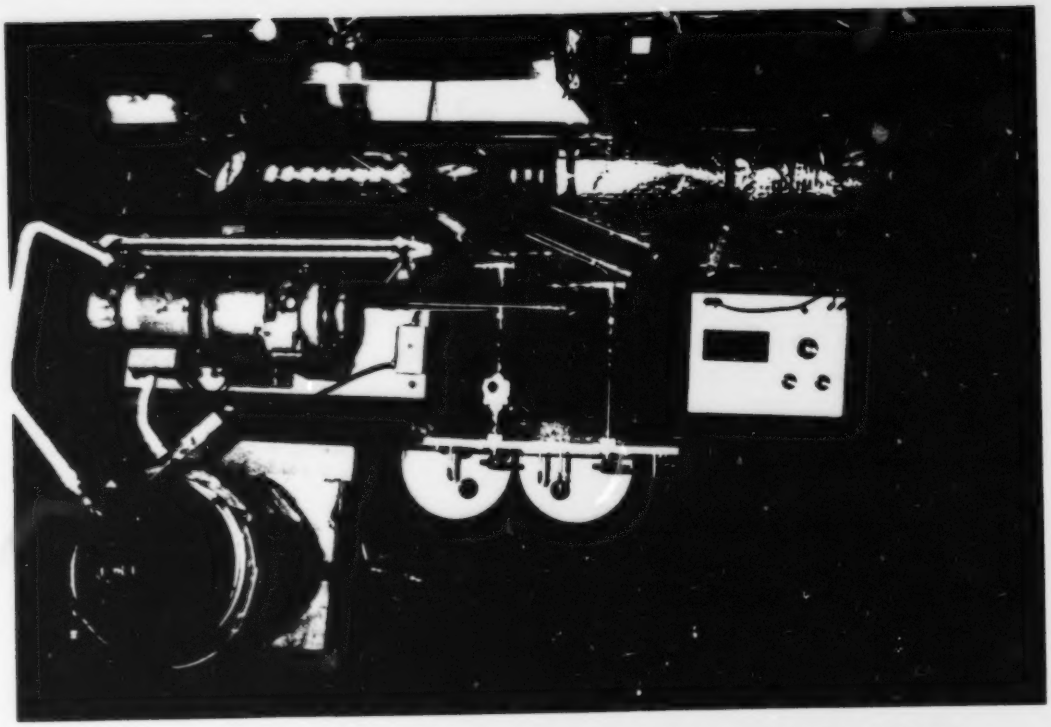


Plate 3: Bench-Top Experimental Coalescer Assembly (Top View)

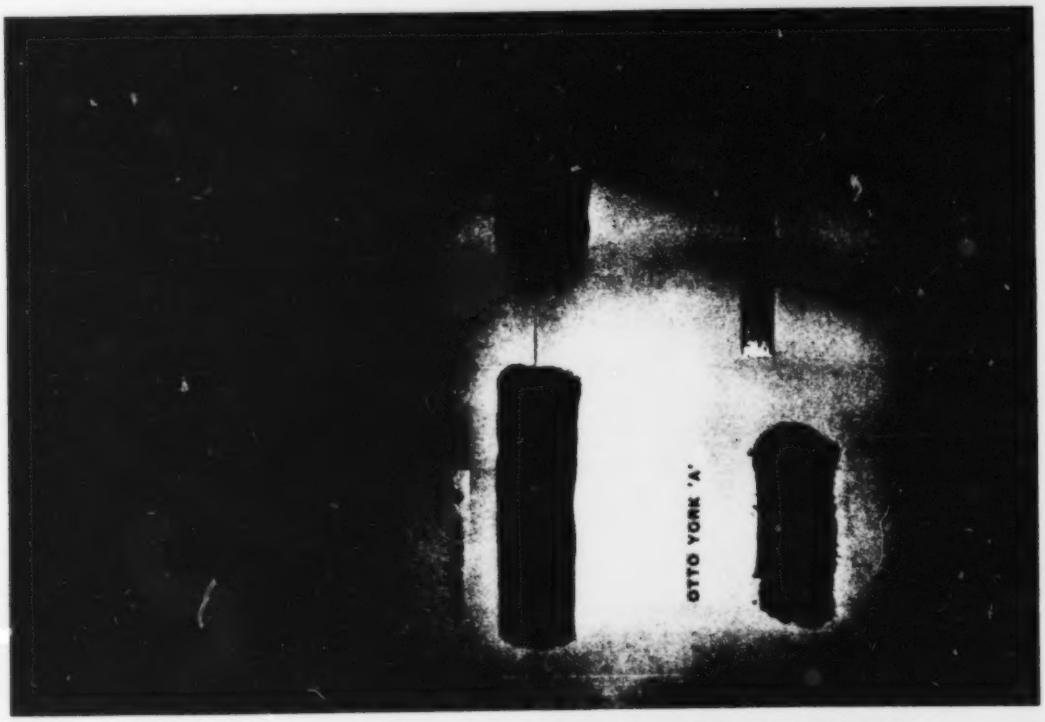


Plate 4: Commercial Coalescing Medium Samples Tested

wrapped around the drum in direct contact with the cylindrical surface and connected in parallel. Maximum total power available from these was 2630 W at the 140 V setting on the variac controller. The feed drum was connected to the pump inlet with a 12.7 mm (1/2") lightly-insulated copper line.

The feed pump used was a Roto-King Model RG-0408 gear pump. It was driven by a 1/2 hp 120 V single-phase sealed electric motor coupled to the pump through a Eurodrive variable-speed belt drive. The variable speed drive enabled manual reduction of the pump speed from 1:1 (1725 rpm) to 1:8 (215 rpm). Pump throughput was calibrated with measured and timed emulsion volumes at the beginning of the test program. The pump and drive were capable of supplying from 1.34 to 6.68 mL/s emulsion to the coalescer.

b. Line Heater

A 12.7 mm (1/2") recycle line led from the pump discharge back to the feed drum to enable operation at flowrates below the pump minimum. A 6.4 mm (1/4") heavily-insulated copper line branched from this recycle line to the line heater. The line heater consisted of two lengths of 9.5 mm (3/8") copper line in series wrapped with 1.2 m × 2.5 cm and 1.8 m × 2.5 cm heavily-insulated heating tapes connected in parallel. Maximum power available from this arrangement was 1650 W. The line heater was wrapped in 2.5 cm thick foil-backed glass fiber insulation.

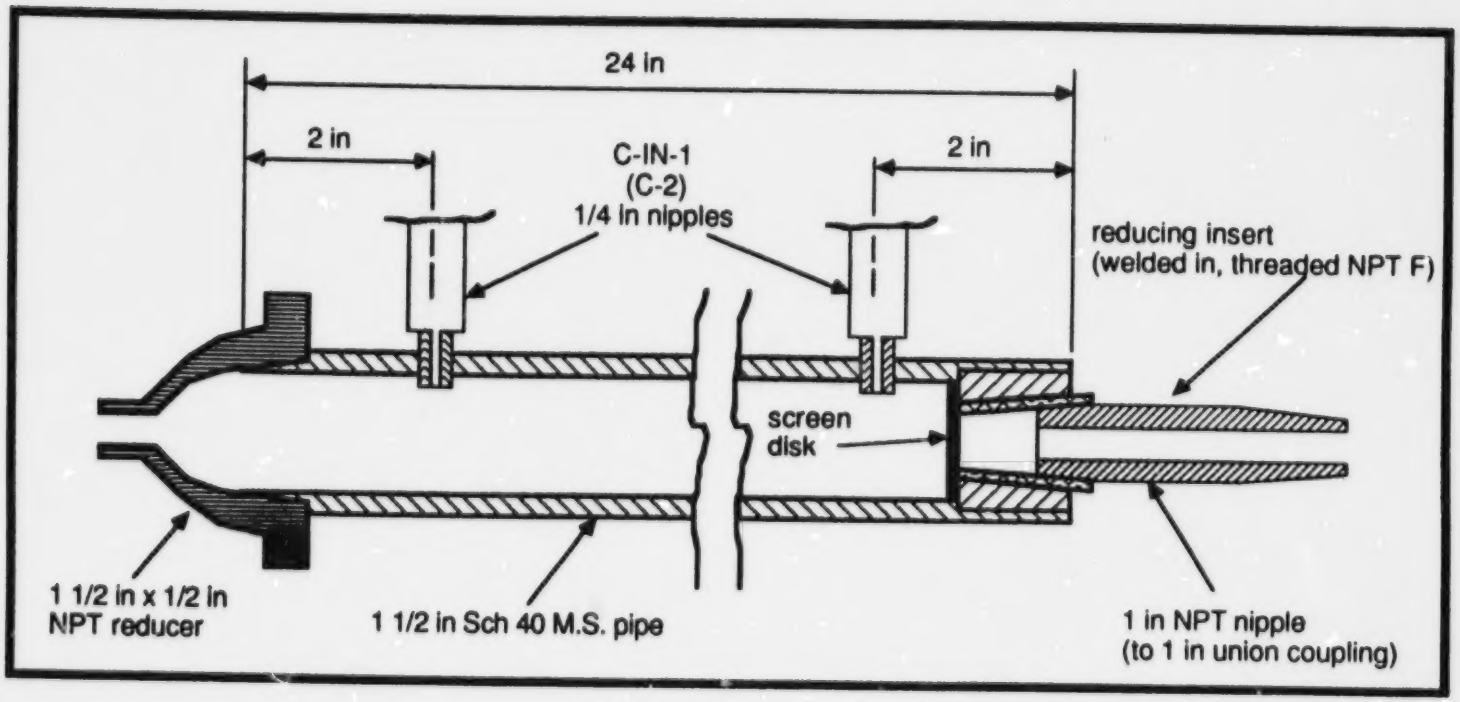
From the line heater, a 6.4 mm (1/4") heavily-insulated copper line led to the sample tap and coalescer inlet. The inlet line was designed with a universal joint to enable the coalescer to be repositioned. Coalescer repositioning was necessary because of the variable length of the separator.

c. Coalescer

The coalescer vessel consisted of a 0.61 m length of 38.1 mm (1.5") Schedule 40 carbon steel pipe (4.09 cm ID). It was threaded with a 1.5" NPT male thread at the inlet to accomodate a 0.5" × 1.5" reducer which constituted the actual inlet end. The outlet was a custom-designed insert bushing welded in place, drilled, and threaded for 1" NPT. This supported the coalescing medium and outlet screen at the downstream end of the coalescer. A pair of 3" × 1" pipe nipples and union coupling connected the coalescer to the separator vessel. The mechanical design of the coalescer is illustrated in Fig. 4.

A 1/4" NPT threaded port was provided on top of the coalescer vessel at locations 5 cm from either end. Into these, a K-type thermocouple was inserted through a tee fitting far enough to protrude slightly into the vessel. A 0 - 1400 kPa steam pressure gauge was supported on the branch of each tee. The coalescer was wrapped with a 2.4 m × 2.5 cm heavily insulated heating tape and covered with 2.5 cm thick foil-backed glass fiber insulation. The

Figure 4: Schematic Cross-Section of Coalescer Vessel



heating tape could provide 1130 W at maximum power.

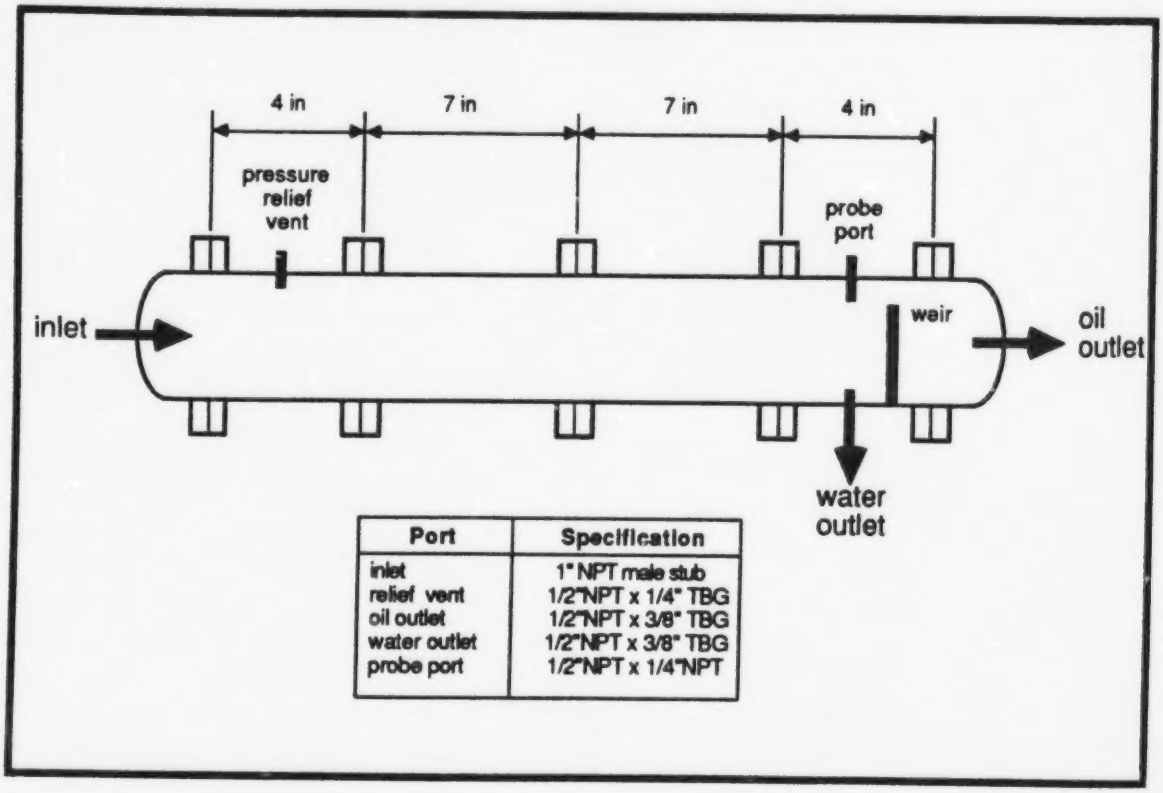
d. Phase Separator

Effluent from the coalescer passed through into a horizontal phase separator. The separator was fabricated from 4" Schedule 80 steel pipe (9.72 cm ID). Minimum total length of the vessel was 40 cm; two flanged inserts of 18 cm each permitted extension of the vessel to the maximum length of 76 cm. The phase separator is illustrated in Fig. 5. Input power of up to 850 W was available from a 1.8 m × 2.5 cm heating tape wrapped around the separator and covered with 2.5 cm thick foil-backed glass fiber insulation.

e. Product Handling

As shown in Fig. 5, separated light-phase product overflowed an 8.5 cm high weir at the end opposite the inlet. An uninsulated 0.95 cm (3/8") copper line led from the light product outlet through the light product chiller to the light-phase product collection drum. Light-phase product flowrate was determined by combined gravitational influence and separator-atmospheric pressure differential. Separated heavy-phase product was drawn from a port in front of the light phase overflow weir at the bottom of the vessel. It flowed similarly through a water-cooled chiller and into the heavy product collection drum.

Figure 5: Schematic Cross Section of Separator



Port	Specification
inlet	1" NPT male stub
relief vent	1/2"NPT x 1/4" TBG
oil outlet	1/2"NPT x 3/8" TBG
water outlet	1/2"NPT x 3/8" TBG
probe port	1/2"NPT x 1/4"NPT

f. Phase Interface Position Control

The phase interface level inside the separator was controlled with a specially built conductivity sensor and solenoid-actuated dump valve on the heavy-phase outlet line. The sensor consisted of a pair of parallel 1 × 2 cm steel plates welded to a pair of rigid wire leads. The leads were supported by a Delrin plug drilled, tapped on the outside for 1/16" NPT, and fitted with a pair of straight connectors to seal the lead passages. The sensor assembly was mounted horizontally on the back of the separator vessel with a 1" NPT connector to permit rotation of the parallel plates into a vertical orientation in order to improve drainage from the the plate gap. The plates were thus positioned at approximately the midpoint of the separator.

The sensor leads were connected to the inputs of a YSI Scientific Model 32 electrical conductivity meter. The amplified output signal from the pen plotter port of the conductivity meter was used as input for a custom-designed dump valve controller logic circuit. The controller circuit was designed with a selector switch to accomodate either phase (oil = low conductivity; saline water = high conductivity) as the heavy-phase. A pair of potentiometers permitted adjustment of the threshold conductivity and the dump time range (seconds to minutes). On triggering, a 120 V 1/4" normally-closed solenoid valve on the heavy-phase outlet line downstream of the manual regulating valve opened fully.

g. Chiller Design

The entire system was designed to operate at temperatures between ambient and 150°C and to mechanically withstand pressures to 1200 kPa, although the separator pressure relief valve was set to open at 900 kPa. The product chillers were sized to reduce the product stream temperatures from 150°C to below 90°C at maximum product flowrate. The chillers were simple shell-and-tube heat exchangers with water as the coolant on the tube side and a separator effluent stream as the process fluid on the shell side. Each was approximately 0.5 m in overall length, with a 0.64 cm (1/4") OD tube and a 0.95 cm (3/8") iron pipe shell. These enabled operation under pressure at temperatures well above the ambient pressure boiling point of water. Stream pressures were dropped to near-atmospheric across manually operated regulating valves downstream of the chillers.

h. Process Measurements

Temperatures were measured at six points in the test apparatus with chromel-alumel (K-type) thermocouples: in the feed drum, in the coalescer vessel at the upstream and downstream faces of the coalescing medium, in the separator, and in the light and heavy-phase product lines between the chillers and the regulating valves. Thermocouple output was amplified and converted to temperature by a DigiTec Model 2780 digital display equipped

with a multi-point rotary switch, manually read and recorded. Pressures were measured at three points: in the coalescer vessel at the upstream and downstream faces of the coalescing medium and in the separator vessel. Pressure measurements were made with Marsh P-0154 pressure gauges with a range of 0 - 1400 kPa in steam service. Measurements were read and recorded manually. Flowrates were measured with a collection vessel, a stop watch, and an electronic balance.

2.3 Emulsion Coalescing Experiment Procedure

An emulsion coalescing experiment consisted of three separate phases: emulsion preparation (as described above), unit start-up and emulsion processing, and post-test evaluation of samples and results. The emulsion processing procedure - the second of the three phases - is described sequentially here:

(1) Preheat feed emulsion to feed temperature (target: 75°C) while circulating through feed pump and recycling to feed drum at maximum rate.

(2) Preheat line heater, coalescer, and separator to process temperature (75 to 125°C).

(3) Adjust pump rate to experimental set-point.

(4) Redirect flow from full recycle to coalescer feed (possibly with partial flow recycle).

(5) Open regulating valves on separator outlet lines fully if ambient pressure test. Close completely if superpressured test.

(6) Allow separator pressure to build to desired value ($P_{v,w}(T_{sep})$ + 140 kPa (20 psi)). Once experimental pressures reached, open light-phase product line regulating valve to bleed air from inside separator while maintaining pressure level.

(7) Open heavy-phase product line regulating valve when separator dump valve automatically actuated first time. Adjust valve setting so that pressure decline in separator does not exceed 70 kPa (10 psi) during heavy-phase dump.

(8) Sample feed and product lines two-to-three times during course of experiment; feed and light-phase product at any time, heavy-phase product when dump valve actuated. Sample volume = 100 - 125 mL.

(9) Record temperatures several times over course of experiment.

(10) Shut-down when feed emulsion supply exhausted. Measure phase product volumes. Clean out drums, drain vessels and measure volume drained, blow out product lines with compressed air and rinse with

solvent (Varsol) to clear valves. Remove and rinse coalescing medium smaples with solvent for future use.

2.4 Procedure for Other Tests

a. Dean-Stark Extractive Distillation

The Dean-Stark distillative method was used to determine the quantity of water in a feed or product emulsion sample. The procedure used for testing the samples from this program is described here:

(1) Weigh emulsion sample and place in round-bottomed flask (total sample if visible phase separation has occured in sample bottle; fractional sample otherwise).

(2) Add equivalent volume of toluene and a few boiling chips (Boil-Easers) to flask. Shake to contact emulsion well with solvent.

(3) Heat on heating mantle to ≈ 150°C for sufficient time to boil off most volatiles (≈ 1 hr).

(4) Record volume collected in condenser side-arm as water.

b. Photomicrography

Slides were prepared for photomicrography by dipping a stirring rod into the fresh sample, placing a droplet on a specimen slide, smearing the droplet with a second slide to distribute the sample over the surface, and covering the smeared sample with a cover slip. Photographs of the emulsion samples were taken as soon as possible following the completion of this preparative procedure.

SECTION 3

EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Emulsion Stability Test Results

Measurements made during the volumetric emulsion stability tests are tabulated in Table 2. Two tests were run: at 75°C and at 95°C. The upper temperature limit was imposed by the water in the constant temperature bath used to heat the cylinder containing the emulsion test sample. Over 6 hours was required for separation of 50% of the water from the emulsion at 95°C. Separated water volume (and separated percentage of total emulsion water) as a function of time is shown in Fig. 6 for both emulsion stability tests.

In order to characterize the stability of the emulsion samples with a single parameter, the phase separation data - transformed to concentration of water remaining in the oil phase as a function of time - were fitted with rate equations of orders ranging from 0 to 2. The best fit to the observed data was with a first-order equation of the form:

$$\ln\left[\frac{C^*_{w,0}}{C^*_{w,t}}\right] = k_1\, t \qquad (1)$$

where the asterisk denotes that the concentration is based on the time-dependant volume of emulsion remaining ($V_{e,0} - V_{w,t}$). In fitting this equation

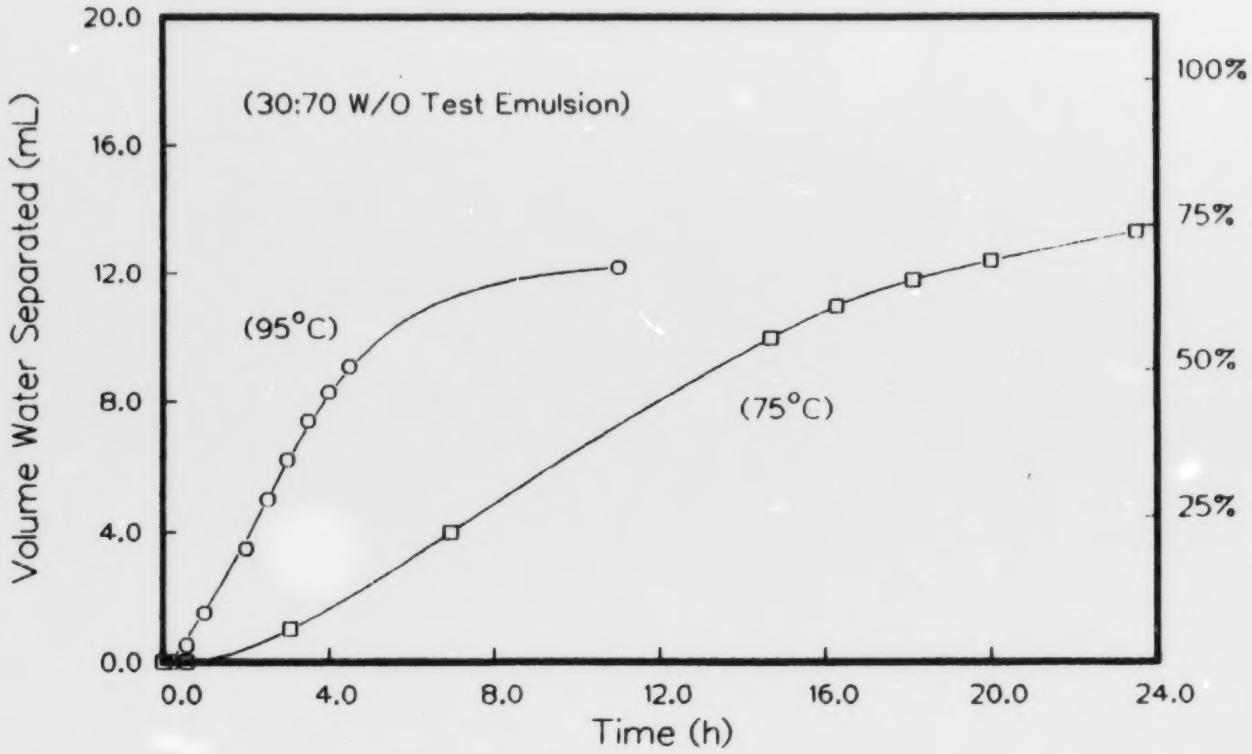
Table 2: Emulsion Stability Test Measurements

COLT Mechanical Emulsion Breaking Test Program

	t (h)	$V_{w,S}$ (mL)	$V_{w,D}$ (mL)	$V_{T,t}$ (mL)	$C_{w,D}$ $(V_{w,D}/V_{T,0})$	$C^*_{w,D}$ $(V_{w,D}/V_{T,t})$	$\ln\left[\frac{C^*_{w,0}}{C^*_{w,t}}\right]$	$1/(C^*_{w,D})$
TEST 1	0.00	0.0	18.0	60.0	0.300	0.300	0.000	3.33
(75°C)	0.57	0.0	18.0	60.0	0.300	0.300	0.000	3.33
1988-06-23	3.07	1.0	17.0	59.0	0.283	0.288	0.040	3.47
	6.95	4.0	14.0	56.0	0.233	0.250	0.182	4.00
	14.68	10.0	8.0	50.0	0.133	0.160	0.629	6.25
	16.27	11.0	7.0	49.0	0.117	0.143	0.742	7.00
	18.12	11.8	6.2	48.2	0.103	0.129	0.847	7.77
	20.00	12.4	5.6	47.6	0.093	0.118	0.936	8.50
	23.50	13.3	4.7	46.7	0.078	0.101	1.092	9.94
TEST 2	0.00	0.0	18.0	60.0	0.300	0.300	0.000	3.33
(95°C)	0.23	0.0	18.0	60.0	0.300	0.300	0.000	3.33
1988-07-08	0.57	0.5	17.5	59.5	0.292	0.294	0.020	3.40
	1.00	1.5	16.5	58.5	0.275	0.282	0.062	3.55
	2.00	3.5	14.5	56.5	0.242	0.257	0.156	3.90
	2.53	5.0	13.0	55.0	0.217	0.236	0.238	4.23
	3.00	6.2	11.8	53.8	0.197	0.219	0.313	4.56
	3.50	7.4	10.6	52.6	0.177	0.202	0.398	4.96
	4.00	8.3	9.7	51.7	0.162	0.188	0.469	5.33
	4.50	9.1	8.9	50.9	0.148	0.175	0.540	5.72
	11.00	12.2	5.8	47.8	0.097	0.121	0.905	8.24

Figure 6: Volume Separated – Emulsion Stability Tests

COLT Mechanical Emulsion Breaking Study



to the measured data, it was necessary to neglect very early-time and very late-time data, as is apparent in Fig. 7. The concentration data are, however, quite linear in the intermediate time region; linearity, as indicated by the r^2 parameter, was 0.999 or higher for both regressions. At 75°C, a value for the rate constant k_1 of 0.059 h^{-1} was obtained from the analysis; the value of the constant from the 95°C test was 0.155 h^{-1}.

As only two stability tests were carried out, the repeatability of the measurements is unknown. No attempt was made to determine the temperature-dependence of the separation rate constant because - with only two data points - the degree of confidence could not be assessed.

3.2 Emulsion Coalescing Tests and Results

a. Coalescing Media

Samples of the five types of commercially-offered coalescing media tested are shown in Plate 4. The samples are shown as provided by the manufacturer with the exception of the York "A" sample, which was tested prior to being photographed. A 15 cm rule is also shown for scale. Properties and dimensions of the media are compiled in Table 3.

For phase-separation tests with the commercial media, cylindrical

Figure 7: First–Order Phase–Separation Rate Functions

COLT Mechanical Emulsion Breaking Study

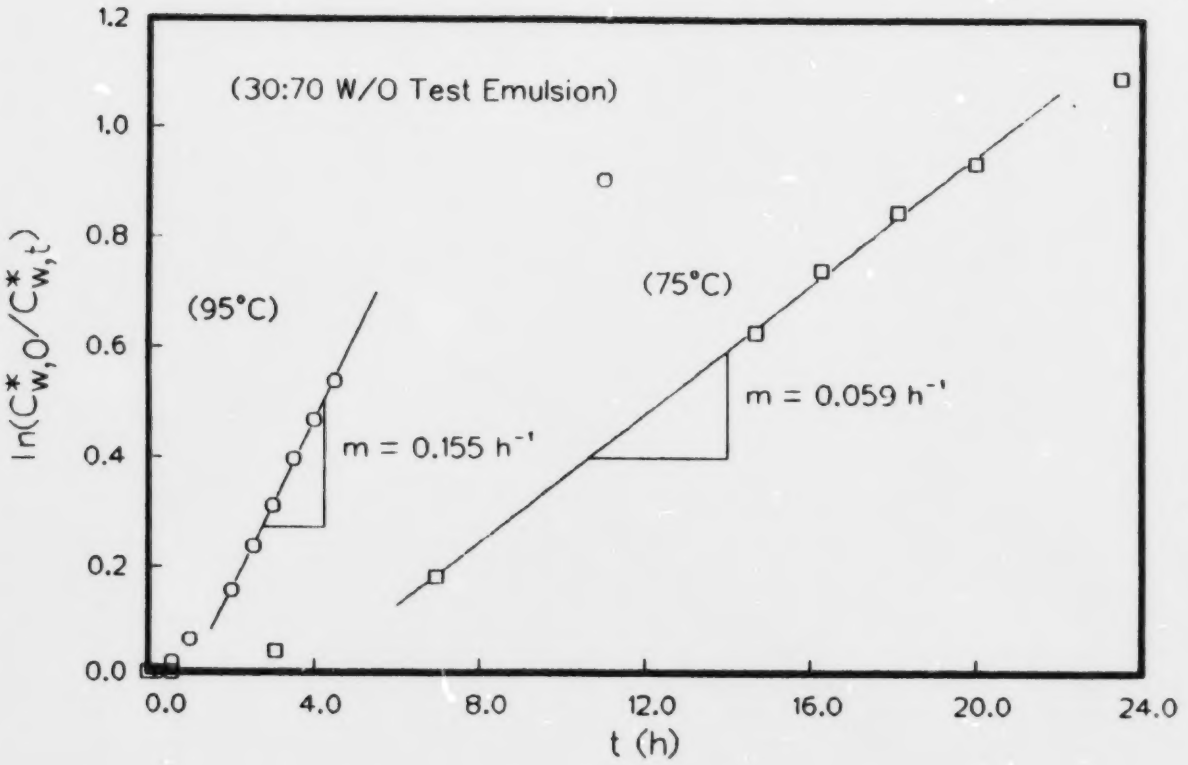


Table 3: Properties and Dimensions of Coalescing Media

Medium Symbol	Manufacturer	Oleophilic Material	Hydrophilic Material	Sample Dimensions (1) Length (*cm*)	Sample Dimensions (1) Diameter (*cm*)	Compressed Density (kg/m^3)	Compressed Voidage (2)
KM-A	KnitMesh Ltd., UK	Hostaflon	SS	15.5	4.3	257	0.964
KM-B	KnitMesh Ltd., UK	PTFE	SS	15.0	4.0	34.5	0.993
KM-C	KnitMesh Ltd., UK	(3)	(3)	15.0	4.0	206	0.960
KM-D	KnitMesh Ltd., UK	fibre (4)	SS	6.5	4.5	222	(5)
OY-A	Otto York Co. Ltd., USA	PTFE	SS	10.5	4.3	257	0.946

Notes

(1) As shipped; uncompressed form - single medium sample.
(2) Estimated from compressed sample volume and weight.
(3) Proprietary information.
(4) Unspecified composition.
(5) Unable to estimate; insufficient information.

samples of a medium were inserted into the upstream end of the coalescer. Sufficient medium was inserted to fill the coalescer vessel entirely, except for the Knitmesh "D" plug sample tests. In that instance, two plugs were inserted and pushed to the downstream end of the coalescer. In all cases, the samples were compressed slightly (≈ -2.5 cm) after insertion into the coalescer vessel by placement of a tubular spacer between the medium and the threaded reducer which comprised the upstream end of the vessel (Fig. 4).

b. Initial (100°C) Coalescing Tests

The initial series of 6 experiments was conducted with a 30% water W/O emulsion, at a moderately high temperature (100°C), at ambient pressure, and with a feed velocity $\bar{u}_f = 3.7\ m^3/m^2\ h$. Recommended superficial feed velocities of one media vendor range from ($\bar{u}_f \leq 2.8\ m^3/m^2\ h$) for coalescence of secondary dispersions ($\bar{d}_p \leq 30\ \mu m$) up to ($\bar{u}_{f,max} = 60\ m^3/m^2\ h$) for primary dispersions of large droplets ($\bar{d}_p \geq 30\ \mu m$). A second reference (Sareen *et al.*, 1966) recommends fluid superficial velocities of 4.5 to 18 $m^3/m^2\ h$) Separator residence time was 36 to 40 minutes.

Results of the 100°C tests are tabulated in Table 4. A total of six tests were run with the 5 commercial media samples and an "empty tube" test (no coalescing medium in the coalescer vessel) for comparative purposes. Conditions were kept as nearly identical as possible for all experiments. None

Table 4: Experimental Measurements - 100°C W/O Coalescing Test Series

COLT Mechanical Emulsion Breaking Test Program

Sample No.	Wt. H_2O + Oil (g)	Vol. H_2O (mL)	Wt.% H_2O (%)	Run Avge. (%)	Conditions	Notes
0614-1-F-1	9.920	2.81	28.33	27.6	(none)	(3)
0614-1-F-2	11.446	3.08	26.91		100 deg.C	(3)
0614-1-L-1	11.810	3.35	28.37	27.2		
0614-1-L-2	13.715	3.56	25.96			
0615-1-F-1/1	20.372	10.50	51.54	28.4	OY-A	(3)
0615-1-F-1/2	15.533	4.40	28.33		100 deg.C	(3)
0615-1-F-2	11.289	3.20	28.35			(3)
0615-1-F-3	11.323	2.24	19.78			(3)
(0615-1-F-3)	74.700	10.50	14.06			(2,3)
0615-1-L-1	20.318	10.00	49.22	37.6		
(0615-1-L-1)	61.500	27.90	45.37			(2)
0615-1-L-2	11.205	3.48	31.06			
0615-1-L-3	11.975	2.98	24.89			
0615-1-H-1	20.297	9.40	46.31	46.3		(4)
(0616-1-F-1)	64.980	16.40	25.24	25.2	KM-A	(1,3)
0616-1-F-2	13.710	3.50	25.53		100 deg.C	(3)
0616-1-F-3	11.672	2.90	24.85			(3)
0616-1-L-1	9.331	2.60	27.86	24.5		
0616-1-L-2	10.717	2.50	23.33			

0616-1-L-3	13.410	3.00	22.37			
0616-1-H-1	13.340	2.95	22.11	22.1		(4)
0616-2-F-1	10.891	3.02	27.73	25.4	KM-B	(3)
0616-2-F-2	13.314	3.34	25.09		100 deg.C	(3)
0616-2-F-3	11.180	2.75	24.60			(3)
(0616-2-F-4)	91.665	22.00	24.00			(1,3)
0616-2-L-1	11.082	2.67	24.09	25.4		
0616-2-L-2	12.815	2.80	21.85			
0616-2-L-3	15.170	4.60	30.32			
0616-2-H-1	13.484	3.55	26.33	26.3		
0617-1-F-1	81.90	30.0	36.6	36.3	KM-C	(1)
0617-1-F-2	88.88	24.0	27.0		100 deg.C	(1)
0617-1-F-3	91.55	41.5	45.3			(1)
0617-1-L-1	100.91	35.0	34.7	32.1		
0617-1-L-2	92.74	28.5	30.7			
0617-1-L-3	84.19	26.0	30.9			
0617-1-H-1	105.76	43.5	41.1	41.1		(3)
0617-2-F-1	77.15	12.0	15.6	17.3	KM-D	(1)
0617-2-F-2	86.64	16.5	19.0		100 deg.C	(1)
0617-2-L-1	97.39	18.0	18.5	16.5		
0617-2-L-2	93.02	13.5	14.5			
0617-2-H-1	89.61	22.0	24.6	24.6		(3)

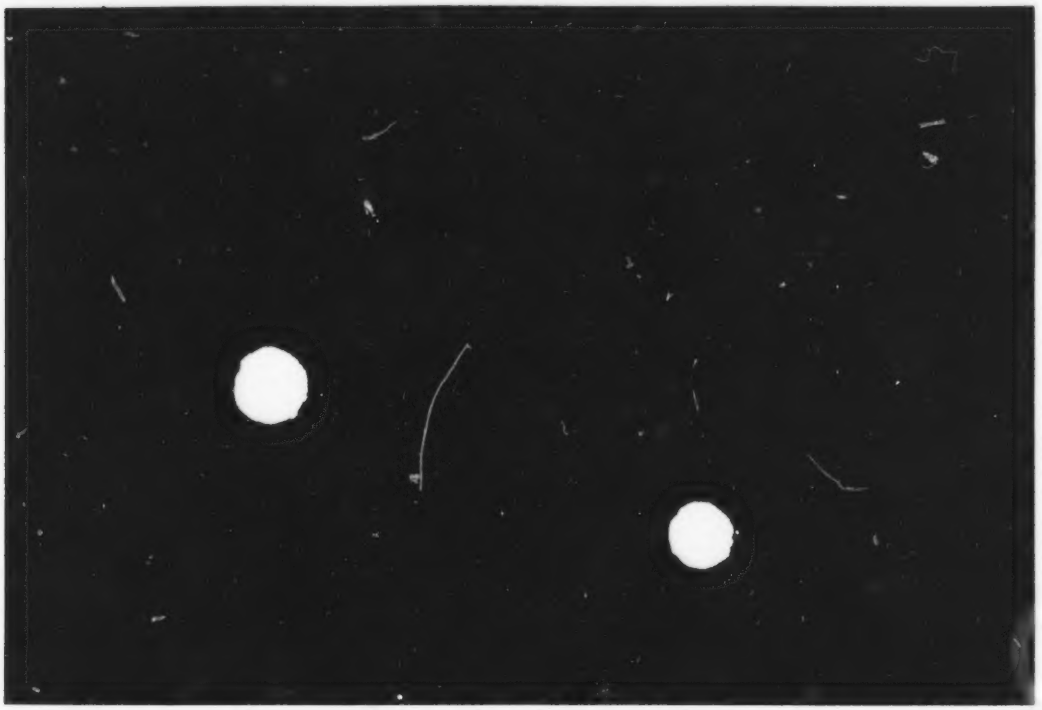
(1) from Sample Set No. 2
(2) re-analyzed - Sample Set No. 2
(3) sampled downstream of line heater
(4) forced-discharge HP sample

of the samples appeared to have any effect whatsoever on the emulsion; the emulsion appeared to emerge in its original condition from the coalescer and separator. This impression was re-inforced by (a) the lack of any free-water production from the heavy phase line in any of the experiments, and by (b) an examination of photomicrographs of the feed and light-phase line product. Plates 5 and 6 show examples of feed and light-phase samples, respectively, at a total magnification of 128. Note the droplet size distribution apparent in both of the plates; the largest droplets do not exceed 20 μm in diameter, and the vast majority are of less than 5 μm diameter, indicating that the emulsification procedure outlined in the preceding section section did indeed create quite stable emulsions. Product receiver drum volumes were not recorded for these experiments, as essentially all of the feed emulsion exited the separator through the light-phase product line. The automatic dump valve on the heavy-phase product line had to be manually actuated to produce any sample whatsoever.

c. Higher Temperature (110, 125°C) Tests

Further tests were conducted, again with the highly-stable 30% water W/O emulsion, and with the same separator volume and emulsion feedrate as in the previous test series at 100°C. The intent was to determine whether increased operating temperature would improve the coalescer performance.

Plate 5: Feed Sample Micrograph - Sample 0621-1-F-2



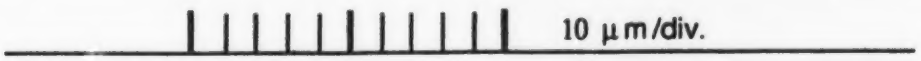


Plate 6: Light-Phase Product Sample Micrograph - Sample 0621-1-L-3

An additional 4 tests were carried out: a side-by-side comparison of "empty-tube" performance (no coalescing medium in the coalescer vessel) with one of the mixed-media mesh samples (KM-A). Tests were conducted at 110 and 125°C and elevated pressures ($p_{min} = p_{v,w} + 10\ \psi$). The results are included in Table 5.

3.3 Discussion of Results

a. Effect of Temperature

At 100°C, no significant phase separation occurred in either the empty tube or in any of the 5 coalescing media tested. The test emulsions were simply too stable to achieve any significant phase segregation during the residence time in the coalescer and separator. Increased operating temperature had a definite effect on the stability of the emulsion. Significant phase separation occurred in tests at both 110 and 125°C. Of greatest importance, however, is that no significant difference could be determined between the separations achieved with the coalescing medium and those with the empty coalescing vessel at either temperature.

b. Effect of Flowrate

Flowrate and fluid velocity were deliberately kept low to avoid the

Table 5: Experimental Measurements - 110, 125°C W/O Coalescing Test Series

COLT Mechanical Emulsion Breeking Test Program

Sample No.	Wt. H_2O + Oil (g)	Vol. H_2O (mL)	Wt.% H_2O (%)	Run Avge. (%)	Conditions	Notes
0621-1-F-1	102.10	28.0	27.4	26.3	(none)	(2)
0621-1-F-2	97.46	24.5	25.1		125 deg.C	(2)
0621-1-L-1	89.52	9.0	10.1	11.6		
0621-1-L-2	92.83	11.0	11.8			
0621-1-L-3	97.97	12.5	12.8			
(0621-1-H-1)			100.0	100.0		
(0621-1-H-2)			100.0			
(0621-1-H-3)			100.0			(3)
0622-1-F-1	97.87	7.5	7.7	9.5	(none)	(2)
0622-1-F-2	88.51	10.0	11.3		110 deg.C	(2)
0622-1-L-1	101.60	7.5	7.4	7.5		
0622-1-L-2	30.46	2.3	7.6			
(0622-1-H-1)			100.0	100.0		
(0622-1-H-2)			100.0			
0624-1-F-1	92.08	27.0	29.3	20.0	KM-A	(2)
0624-1-F-2	98.55	10.5	10.7		110 deg.C	(2)
0624-1-L-1	91.21	15.5	17.0	15.0		
0624-1-L-2	93.99	12.3	13.1			
0624-1-H-1	87.05	31.5	36.2	68.1		(3)

(0624-1-H-2)			100.0			(3)
0627-1-F-1	89.71	27.5	30.7	27.5	KM-A	(2)
0627-1-F-2	86.40	19.5	22.6		125 deg.C	(2)
0627-1-F-3	102.63	30.0	29.2			(2)
0627-1-L-1	91.56	7.3	7.9	9.5		
0627-1-L-2	86.71	8.5	9.8			
0627-1-L-3	87.73	9.5	10.8			
(0627-1-H-1)			100.0	100.0		(3)

(1) sampled downstream of line heater
(2) sampled from feed drum
(3) forced discharge HP sample

Table 5 (cont'd): Material Balance Calculations - 110, 125°C W/O Coalescing Test Series

COLT Mechanical Emulsion Breaking Test Program

	Run No.	$V_{F,t}$ (L)	x_F	$V_{F,i}$ (L)	$V_{L,t}$ (L)	x_L	$V_{L,i}$ (L)	$V_{H,t}$ (L)	x_H	$V_{H,i}$ (L)	TB (%)	CB_i (%)	$R_{w,1}$ (%)	$R_{w,2}$ (%)	$R_{o,1}$ (%)	$R_{o,2}$ (%)
O	0622-1	12.2	0.905	11.0	9.4	0.925	8.7	2.8	0.000	0.0	100.0	78.8			78.8	100.0
W	- /110		0.095	1.2		0.075	0.7		1.000	2.8		302.4	241.59	79.9		
O	0624-1	11.0	0.800	8.8	7.9	0.850	6.7	3.1	0.000	0.0	100.0	76.3			76.3	100.0
W	KM-A/110		0.200	2.2		0.150	1.2		1.000	3.1		194.8	140.91	72.3		
O	0621-1	11.5	0.737	8.5	3.0	0.884	2.7	8.5	0.000	0.0	100.0	31.3			31.3	100.0
W	- /125		0.263	3.0		0.116	0.3		1.000	8.5		292.5	281.04	96.1		
O	0627-1	12.0	0.725	8.7	9.5	0.905	8.6	2.5	0.000	0.0	100.0	98.8			98.8	100.0
W	KM-A/125		0.275	3.3		0.095	0.9		1.000	2.5		103.1	75.76	73.5		

potential problem of redispersion of aggregated or coalesced water (dispersed-phase) droplets. Inertial impaction has been previously described as a significant coalescing mechanism only for larger diameter droplets (primary dispersions) (Bayley and Davies, 1978; Hazlett, 1969; Sareen *et al.*, 1966). For dispersions with smaller mean droplet diameters, coalescence occurs via other mechanisms (Bayley and Davies, 1978). The microphotographic plates clearly demonstrate that the mean droplet diameter in the created emulsions is of the order of 5 μm or less. Hence, increased fluid velocity (and flowrate) should not enhance the coalescence performance of the mesh media. This remains to be demonstrated.

c. Effect of Medium

No significant differences were found between any of the media tested. However, this result may change at a higher operating temperature with significant phase separation in the separator residence time.

d. Effect of Separator Residence Time

Separator residence time was not felt to significantly affect the results of this test program. These experiments were carried out on a comparative basis, looking for differences between conventional gravitational settling and mesh-medium enhanced phase segregation. Moreover, separator residence

time has not been considered a significant variable affecting the extent of phase separation because of the elimination of the coalescence band by mixed-media coalescers (Bayley and Davies, 1978). Coalescence and phase segregation in such media is reported to take place within the medium itself.

e. Emulsion Type

Only one type of emulsion was tested during this test program. This was deliberately chosen at the outset of the program to be the more difficult of the two types to separate. Tests with an oil-in-water (O/W) emulsion had been planned. Emulsification of the oil-water mixture would follow a similar procedure to that outlined for W/O emulsion with the addition of an appropriate emulsifying agent to promote dispersion of oil droplets. Emulsions of similar stability to that of the created W/O emulsions could thus be produced. The mean droplet diameter of these water-external emulsions of equivalent stability would necessarily be smaller because of the lower continuous-phase viscosity, so that inertial impaction would also not be a significant coalescence mechanism in this case.

f. Potential Fluid Bypassing

A major concern during the design of the coalescer vessel was to accomodate frequent changes of the contained coalescing medium, yet

prevent fluid bypassing of the medium within the vessel along the tube walls. Measures taken to inhibit such bypassing included insertion of coalescing medium elements with diameter greater than that of the vessel ID and compression of the coalescing medium *in situ* by insertion of tubular spacers between the inlet end cap and the upstream element face. Despite these measures, however, fluid bypassing of the medium elements, wholly or partly, may still have taken place. No tests were carried out to determine whether this was occurring. Fluid pressure drops across the coalescer vessel were generally quite low for all of these experiments (in the order of 1 - 2 kPa). A significant pressure drop (7 kPa) was measured during only one test: 2 KM-C (Knitmesh DUSEC fibrous coalescer cartridge plug cores) in series with W/O emulsion at 100°C and $1.34 \times 10^{-6}\ m^3/s$ feedrate. It was felt, therefore, that bypassing was probably not significant with such low pressure differentials across the coalescing elements typically.

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

(1) Coalescing tests with 5 different samples of mixed-wettability emulsion coalescing media were carried out on a highly-stable heavy oil emulsion at 100°C and atmospheric pressure in a bench-scale coalescer-separator. No significant difference was found in phase separations achieved with any of the 5 media samples compared with that due to gravitational settling alone.

(2) Further tests with a knitted mixed-wettability medium were carried out at temperatures of 110 and 125°C and pressures above the vapour pressure of water at those temperatures. Comparison of the phase separation achieved with the medium and that achieved without any coalescing medium present again showed no difference which could be attributed to an enhancement of the rate of phase separation by the coalescing medium.

(3) Further experiments will be necessary to demonstrate what - if any - potential there is for coalescence of heavy oil emulsions with mixed-wettability knitted or fibrous media.

4.2 Recommendations

(1) Further tests with W/O emulsion should be carried out to evaluate the performance of the media samples as yet untested at temperatures above 100°C.

(2) Tests with O/W emulsion should be conducted to determine whether the phase separation rate in that system is enhanced with the mixed-composition coalescing media.

(3) A residence time test should be carried out on the coalescer-separator to ensure that the fluid pumped into the coalescer is not bypassing the coalescing medium along the walls of the vessel.

(4) Final conclusions about the ultimate potential for coalescing heavy oil emulsions with mixed-wettability knitted media should be drawn at the completion of the recommended tests.

4.3 Acknowledgements

A great many people assisted in various ways in this project. There were many from private industry who contributed materially to the research effort Among them were Dr. Graham Davies and J.G. Lewis, Knitmesh Ltd., South Croyden, Surrey, UK, Allen Neamy and Michael McGuire, Glitsch Canada Ltd., Toronto, ON, Steve Savage, Otto York Company Ltd., Parsippany, NJ, Garret Brown, Petroferm Inc., Calgary, Alberta, and especially Chris Young, Legrand Industries Ltd., Calgary, Alberta, who took a personal interest in the design of the experiments. Dan Fantini of the Chemical Engineering Department workshop at the University of Calgary fabricated the pressure vessels for the test loop in exemplary fashion.

SECTION 5

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